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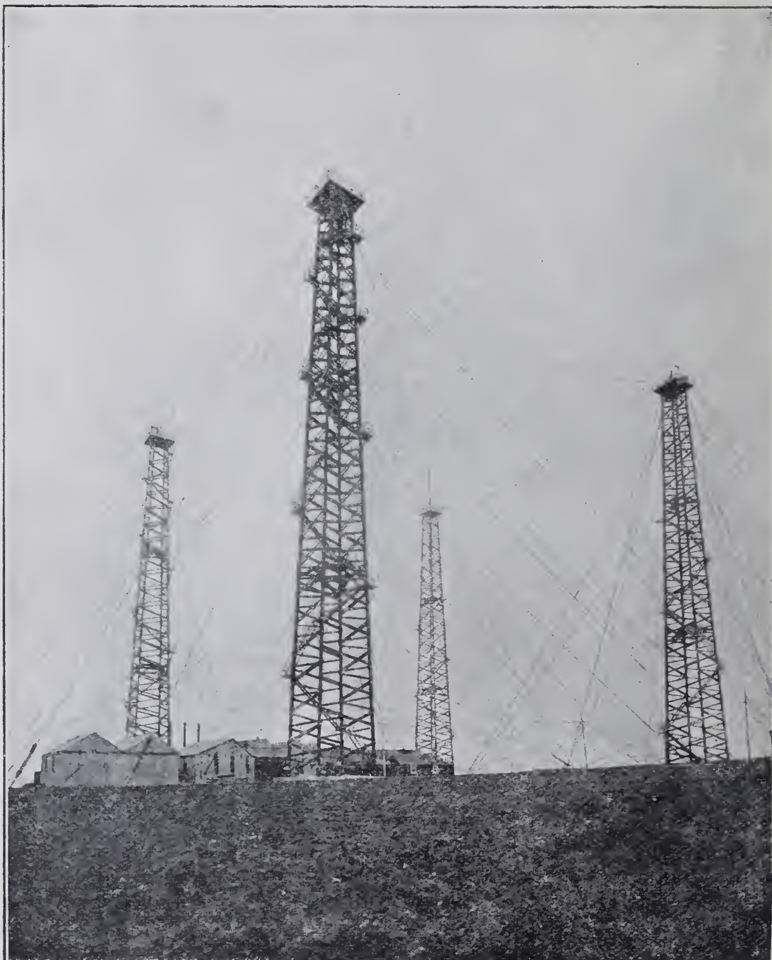

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The Marconi Radiotelegraphic Station at Poldhu, Mullion, Cornwall, England, for Long-distance Transoceanic Wireless Telegraphy, showing the Lattice Towers, 210 feet in height, for supporting the Antennæ.

THE PRINCIPLES OF

ELECTRIC WAVE TELEGRAPHY AND TELEPHONY

BY

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PREFACE TO THE SECOND EDITION

In the four years or more which have elapsed since the publication of the first edition of this Treatise on Electric Wave Telegraphy immense progress has been made in the art and science of Radiotelegraphy, and at the same time the literature in connection with it has become very extensive. A large number of books in different languages have been published, dealing more or less completely with the history and methods for conducting Telegraphy through space without interconnecting wires, and much new practical and scientific knowledge has been accumulated. In preparing, therefore, a second edition of the present book, extensive additions have been made to bring it up to date, and the opportunity has been taken of re-writing much of the original matter so as to remove errors which the criticism of others or of the Author himself had detected. The treatment of the purely historical side of the subject has been, as far as possible, restricted. The practical radiotelegraphist is not at the present time so much interested in general descriptions of inventions and systems, some of which may have become antiquated, and others never developed to the point of practical utility, as he is in a careful analysis of the scientific phenomena, and especially in detailed descriptions of the appliances and methods involved in modern practical Radiotelegraphy, and also in the processes of measurement involved. During the ten years between 1900 and 1910 the Author has been many times called upon to give University Courses or Cantor Lectures at the Society of Arts, London, and Discourses at the Royal Institution of Great Britain, on the subject of Radiotelegraphy, and the present Treatise is based to a large extent upon the subject-matter of the Lectures so delivered. During that time, however, the art of Radiotelephony has been developed as an extension of Radiotelegraphy, and the title of the book has therefore been amplified to include the principles of Radiotelephony as well as Radiotelegraphy, and a short chapter on the former subject being added. In so doing the aim of the Author has not been to give the most complete description of every appliance known or patented, but to deal chiefly with the scientific principles

underlying the art, the theory of the operation of the instruments employed, and especially with the quantitative aspect of the subject, and the methods of measurement which are used in a metrical estimation of the quantities and effects concerned. An enormous amount of research has been carried out in the last ten years on the subject of electromagnetic waves and their application to telegraphy and telephony, and the specifications filed in the Patent Office in various countries bear record to the amount of ingenuity and thought that has been spent in the endeavour to utilize this scientific knowledge for practical purposes.

The extent and importance of Radiotelegraphy in connection with modern life is shown by the degree to which it has been made the subject of patents, of legislation, and of International Conferences, as well as in the attention given to the matter in the daily press.

For the convenience of radiotelegraphists a reprint of the Wireless Telegraphy Act of Great Britain, 1904, is given in the Appendix, and a reproduction of the English translation of the Service Regulations of the International Radiotelegraphic Convention of 1906, made by Mr. G. R. Neilson of the Eastern Telegraph Company, and by kind permission taken from the complete English translation which he made of the *Proceedings of the International Radiotelegraphic Conference of Berlin*, sitting in 1906, officially accepted by H.M. Postmaster-General and published by *The Electrician Printing and Publishing Company* of London.

Invention is, however, progressing so rapidly, even now, in connection with the subject, and the amount of work that has been done is so large, that any attempt to present an account of the subject must necessarily be imperfect in many respects. The quantitative aspect of the subject is, however, of special importance at the present time. There comes a stage in the development of the technical applications of scientific discoveries when exact measurement is the very life and soul of further achievements, and when empirical methods and personal skill have to be replaced by careful predetermination and precise measurement. Hence considerable space has been occupied in the present Treatise with the theoretical treatment of that part of the subject which is necessary for a full quantitative knowledge of it, and also for effecting improvements.

Electric or Hertzian Wave Telegraphy, now called Radiotelegraphy, was for some time regarded as the Cinderella of Telegraphy by her two older sisters, Land and Submarine Telegraphy. Events, however, have long since justified the opinions formed by many persons who witnessed the early and original work of Commendatore G. Marconi (amongst whom the Author may include himself) that the form of wireless telegraphy which unquestionably originated with him was destined to be of the very greatest utility.

Its supremely important application in connection with naval operations and ordinary supermarine communication has given it a unique position in connection with our means of communication through space, and its vast utility and importance have been again and again demonstrated by the aid which it has rendered in saving life at sea. The great achievement of bridging the Atlantic with electromagnetic waves and establishing commercial communication across it by Radiotelegraphy, is an event in connection with which Mr. Marconi's name will be ever memorable, and it can hardly be doubted that even the present achievements of Radiotelegraphy will be thrown into the shade by future advances. There is, however, great difficulty in appraising the value of new schemes and appliances which are from time to time brought forward, and the perusal of Patent Specifications or descriptions of apparatus in the technical journals seldom affords the means of forming a correct estimate of the real value in practice of the processes or appliances described. Nevertheless the fundamental principles of the subject are now fairly well fixed, and it is hoped that the present work in its amended and extended form will be found of assistance as a text-book to those who are engaged in practically operating and developing methods of Radiotelegraphy by presenting in a compact form information, data, and formulæ which are essential in connection with its practical operations and scientific progress.

The writer cannot forbear to mention his obligations to the writings of Lord Kelvin, Lord Rayleigh, Sir Joseph Thomson, Sir Joseph Larmor, Professor Poynting, and others, in connection with parts of the book. In addition to the epoch-making papers of Hertz, the works of many Continental writers, such as Drs. Drude, Wien, Zenneck, Bjerknes, Slaby, Braun, and Seibt, have been sources of valuable information, and where limitation of space has compelled brevity, reference has been made to the original scientific memoirs or books.

The Author desires also to place on record his obligations to the following societies, authors, firms, publishers, and proprietors of journals who have kindly permitted blocks and diagrams belonging to them to be reproduced :—

To the Royal Society, as well as to Professor Karl Pearson, F.R.S., and Miss Alice Lee, B.Sc., for permission to use the diagrams in Plates II., III., IV., and V., and also to Professor A. E. H. Love, F.R.S., for diagrams in Plate V. at the end of Chapter V.; also to Dr. F. Hack for the diagrams in Plate VI., taken from his paper in the *Annalen der Physik*. To Admiral Sir Henry Jackson, F.R.S., R.N., for the use of diagrams and copious extracts from his paper in the *Proceedings of the Royal Society*, abstracted in Chapter IX. To the Physical Society and Mr. W. Duddell for a similar courtesy. To

the *Journal de Physique* and Dr. Hemsalech for the blocks of Figs. 19, 20, and 21 of Chapter I. To the Society of Arts for permitting the use of numerous diagrams taken from reprints of the Author's Cantor Lectures, and to the Institution of Electrical Engineers for the same kindness. Also to the proprietors and publishers of *The Electrician*, *The Philosophical Magazine*, *The Electrical Review*, *Electrical Engineering*, *The Electrical Magazine*, *Technics*, and *The Electrical World of New York*, for permission to use many illustrations which have appeared in their books or journals, and are duly acknowledged in their proper places. To Commendatore G. Marconi and Marconi's Wireless Telegraph Company, Mr. Anders Bull, Dr. J. Zenneck, and to Messrs. Enke, of Stuttgart, to Professor G. W. Pierce and the Editors of the *Physical Review* for likewise permitting the reproduction of views or diagrams which have appeared in papers or books by them respectively. Various firms have obliged the Author by allowing the use of illustrations taken from their trade circulars, *e.g.* the Marconi Company for many diagrams of Marconi apparatus ; Messrs. Isenthal & Co. for the diagrams of the Grisson Electrolytic Interrupter ; Messrs. K. Schall, the use of blocks of Figs. 37, 39, 48, 54, 56, 57, and 58 in Chapter I. ; the Cambridge Scientific Instrument Company, the block of the Duddell Thermoammeter in Chapter VI., and Messrs. Hartmann, Braun & Co. and Mr. Leslie Miller identical favours. To these and others who have assisted in rendering it possible to illustrate the descriptions in the text fully the Author desires to return his thanks, as well as to those who have assisted him in reading the proofs.

J. A. F.

THE PENDER ELECTRICAL LABORATORY,
UNIVERSITY COLLEGE, LONDON,
August, 1910.

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LIST OF PLATES

ERRATA.

THE reader is requested to make the following corrections :—

Pages 34 and 35, under Figs. 34 and 35,

instead of	Gehrche
read	Gehrcke

Page 136, line 7 from bottom,

instead of $$L' = 2l\left(220{\cdot}364 \log \frac{l}{d} - 2{\cdot}853\right) \text{ for a square}$$

read $$L' = 2l\left(2{\cdot}3026 \log_{10} \frac{4l}{d} - 2{\cdot}853\right) \text{ for a square}$$

Page 273, in the formula two lines above formula (107), in the last term,

instead of	$\sqrt{2qa} \cos (qt + \phi)$
read	$\sqrt{2qa} \cos (qt - \phi)$

Page 296, last line,

instead of	attenuation factor
read	attenuation constant

Page 297, first line,

instead of	wave length factor
read	wave length constant

Page 701, line 4 from top,

instead of	$\frac{2\phi^2\pi_3}{r^3\lambda^3}$
read	$\frac{2\phi^2\pi^3}{r^2\lambda^3}$

THE PRINCIPLES OF

ELECTRIC WAVE TELEGRAPHY AND TELEPHONY

PART I.—ELECTRICAL OSCILLATIONS

CHAPTER I

THE PRODUCTION OF HIGH FREQUENCY CURRENTS AND ELECTRIC OSCILLATIONS

1. High Frequency Electric Currents—Damped and Undamped Electric Oscillations.—An alternating electric current is defined to be one which periodically changes direction in its circuit. For a certain time it flows in one direction in some conductor with varying strength, and then reverses and flows for an equal time in the opposite direction. The time in fractions of a second which elapses between the commencement of the current in one direction and beginning again in the same direction is called *a complete period* or cycle, and will be denoted in this treatise by the letter T. The number of complete periods per second is called *the frequency* of the current, and is denoted by n. The quantity $2\pi n$ or $\frac{2\pi}{T}$ is of the nature of an angular velocity, and will be represented by the letter p. It is also the number of periods in 2π seconds.

We have furthermore to distinguish between the *instantaneous value* of the current, or its value at any instant, and the *maximum value.* The former will be denoted by a small letter such as i, whilst the maximum value of the same quantity during the period will be represented by a large letter I of the same type.

A *high frequency alternating electric current* may be defined to be an alternating current of which the frequency is reckoned in thousands. There is no absolute demarcation between high and low frequency. The terms are of course relative. If, however, the frequency is such that the number of periods per second is, say, 1000 or upwards, then it would generally be called a high frequency current, whereas if the frequency was such as to be reckoned in hundreds, or less than a hundred, it would in general be called a low frequency current.

An *electric oscillation* may be defined to be an alternating electric current of extremely high frequency reckoned, say, in hundreds of

thousands or millions per second, but here again the distinction between so called high frequency electric currents and electric oscillations is more a matter of terminology than any precise difference in frequency. We are, however, concerned with two classes of electric oscillations, the difference between which is important. In one case the oscillations or high frequency currents continue with undiminished amplitude or maximum value. They are then called *undamped* or *persistent oscillations*. If, on the other hand, the oscillations after beginning with a certain amplitude die away, then cease, and after a time begin again with the original amplitude, they are called *damped oscillations*, and each group is called *a train of oscillations*. If the decay of amplitude in each train is very rapid, it is called a *strongly damped* oscillation train, and if the rate of decay is small, it is said to be *feebly damped*.

We may graphically represent a high frequency electric current or undamped electric oscillation in the usual manner by a repeated sinoidal curve, since in nearly all the cases likely to occur in practice the variation of current from moment to moment during the complete period is a simple sine function of the time. Hence we may proceed as follows: Let a horizontal line AX (see Fig. 1) be taken as a time

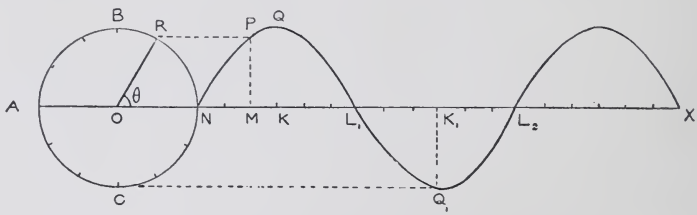


Fig. 1.—Delineation of a Simple Periodic or Sine Curve.

axis, and equidistant points, N, L_1, L_2, X, etc., set off so that distances such as NL_2 or L_1X represent one complete period denoted by T.

Then with some point O in this line AX as centre describe a circle ABN. Let the radius OR of this circle be taken to represent, to some suitable scale, the maximum value of the current during the period. Imagine the radius OR to revolve in a counter-clockwise direction with a uniform angular velocity. Let a horizontal (dotted) line, RP, be drawn at every instant through the extremity of the radius OR. Let another point, M, be supposed to move uniformly along OX, and through it a vertical (dotted) ordinate, MP, be drawn. Let the point M move uniformly through a distance NL_2 in the time taken by the radius OR to revolve once with uniform angular velocity. Assume that OR starts from the position ON, and that the point M also starts from N. Then the locus of the point of intersection P of the vertical ordinate MP with the horizontal line RP will trace out a sinoidal curve, NQL_1Q_1. The length of the ordinate MP will always be equal to the radius of the circle OR multiplied by the sine of the *phase angle* RON $= \theta$. Let the radius of the circle be denoted by I taken to represent the maximum value of the current during its period. Let the radius OR revolve through the angle RON $= \theta$ in the time t with angular velocity p. Hence $\theta = pt$, and if we denote

MP by i, then i is the instantaneous value of the current, and we have—

$$i = I \sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The value of the maximum current I is called the *amplitude* of the oscillation, and the angle pt is called its *phase*. The above expression (1) is therefore the equation of the wavy curve, called a *sine curve*, and is also the analytical expression for a high frequency alternating current, or persistent, or undamped electric oscillation.

We can in the same manner describe a line representing graphically the nature of a damped electric oscillation if we employ a *logarithmic spiral* instead of a circle in a construction similar to that in Fig. 1.

A logarithmic spiral is the curve described by the extremity of a radius vector, the length of which varies so that the logarithm of its length bears a constant ratio to the phase angle the radius vector makes with some fixed straight line. Thus in Fig. 2 the spiral curve is described by the extremity R of a radius OR ($= r$) which revolves uniformly round O, the length OR varying so that the ratio of log r

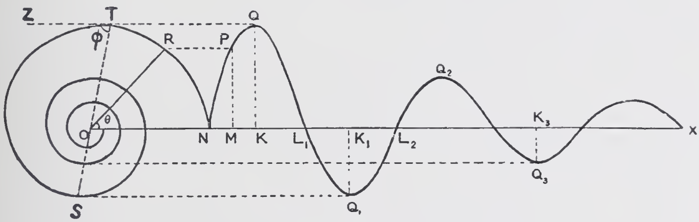


Fig. 2.—Delineation of a Damped Periodic Curve.

to the angle RON ($= \theta$) is constant. Hence the polar equation of the left-handed logarithmic spiral as drawn is $r = a^{-\theta}$, where a is some constant.

The exponent has a negative sign, because r diminishes as θ increases in the case of the spiral as delineated. Suppose, then, that we draw a time axis, OX, and assume a point, M, to move uniformly along it. Also let the radius vector OR move counter-clockwise with a uniform angular velocity. Let a perpendicular MP drawn through M move with it, and through R draw a horizontal line, RP. The locus of the point of intersection P, of the lines RP and MP as the points R and M move in their respective modes, will describe a decrescent wavy line. The equation of this line is found as follows:—Since the angle RON $= \theta$, the ordinate MP $= r \sin \theta$. Also $r = a^{-\theta}$. Hence if we write i for MP, we have—

$$i = a^{-\theta} \sin \theta$$

Let p be the angular velocity of OR. Accordingly, if OR moves through the angle RON in a time t, we can write pt for θ. Also it is convenient to substitute $I\epsilon^{-at}$ or $I\epsilon^{-kpt}$ for $a^{-\theta}$, where ϵ is the base of the Napierian logarithms, and I, a, or k are certain constants.

We then obtain the equation of the wavy line NQQ_1Q_2 in the form—

$$i = I\epsilon^{-at} \sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and this therefore is the mathematical expression for a damped electric oscillation.

If I_1 denotes the maximum value KQ of the first oscillation, I_2 that of the second K_1Q_1 in the opposite direction, and so on; then it is easy to see that i has the value I_1, when $t = \frac{\phi}{\pi}\frac{T}{2}$, and the value I_2 when $t = \frac{\phi}{\pi}\frac{T}{2} + \frac{T}{2}$, where ϕ is the angle TON = OTZ (see Fig. 2), and $\tan\phi = \pi/\delta = p/a$. Hence it follows by substitution in (2) that,

$$\frac{I_1}{I_2} = \epsilon^{a\frac{T}{2}} \text{ or } \log_\epsilon \frac{I_1}{I_2} = \frac{aT}{2} = \delta$$

The quantity $\frac{aT}{2}$ or δ is called the *logarithmic decrement of the oscillations per half period.* The quantity $\epsilon^{-\delta}$, where ϵ is the base of Nap. logs, is called *the damping per half period.*

Hence we have—

$$a = 2n\delta = 2n \log_\epsilon \frac{I_1}{I_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

We can therefore write the equation of a damped electrical oscillation in one of three equivalent forms, thus—

$$\left.\begin{aligned} i &= I_1 \frac{\epsilon^{a\frac{\phi}{\pi}\cdot\frac{T}{2}}}{\sin\phi}\epsilon^{-at}\sin pt \\ i &= I_1 \frac{\epsilon^{\delta\phi/\pi}}{\sin\phi}\epsilon^{-at}\sin pt \\ i &= I_1 \frac{\epsilon^{-a\left(t-\frac{\phi}{\pi}\cdot\frac{T}{2}\right)}}{\sin\phi}\sin pt \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The ratio of one maximum oscillation to the next in the opposite direction is that of ϵ^δ to unity.

Some writers define the logarithmic decrement to be the Napierian logarithm of the ratio of two successive oscillations in the same direction that is separated by one whole period. In that case the symbol taken for it is equivalent to 2δ as used above.

2. The Practical Generation of Undamped and Damped Electric Oscillations.—A number of arrangements have been devised for generating high frequency currents and electric oscillations. Some of these processes create damped and some undamped oscillations. The oldest of these methods is that in which the oscillatory discharge of a condenser is employed to create intermittent trains of damped oscillations. Other well-known appliances are available for the production of undamped oscillations, viz. the high-frequency alternator, the direct current electric arc shunted by an inductive resistance in series with a capacity, and the pulsatory or

variable condenser. The high frequency alternator is more especially applicable for the production of high frequency alternating currents, and the arc methods for the generation of undamped electric oscillations. It is convenient to discuss these in the following order: (1) high frequency alternators; (2) the production of damped oscillation by condenser discharges; (3) the generation of undamped oscillations by the electric arc.

3. Production of High Frequency Currents by High Frequency Alternators.—Machines for the direct production of undamped high frequency alternating currents are called *high frequency alternators.* Not very many of these have been constructed, and until recently the highest frequency obtained by such mechanical appliances has not exceeded 10,000 periods per second. For much of the work in radiotelegraphy and radiotelephony a far higher frequency, at least 30,000, is required, but the mechanical difficulties connected with the production of an alternator for such frequency are considerable and are as yet hardly overcome except for machines of very moderate power.

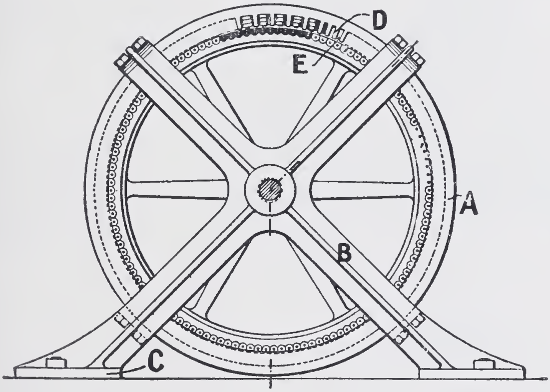


FIG. 3.—Tesla High Frequency Alternator. (*Side view.*)

Designs for high frequency alternators began to be considered about 1889 or 1890, when attention was being directed to arc lighting by alternating currents. It had been found that most forms of alternating current arc lamp produced a disagreeable hum when actuated by an alternating current of a frequency of the order of 100. The notion therefore arose that if a frequency could be used higher than that of the highest audible note, the defect would be annulled. Prof. Elihu Thomson and Mr. Nikola Tesla were probably the first to construct such alternators, and Tesla, finding that he had in this machine a source of electric current capable of exhibiting many interesting electrical effects, pursued the subject and devised several forms of alternator capable of producing alternating currents of a strength of 10 amperes or so, having a frequency as high as 12,000 complete periods per second.

One form of Tesla high frequency alternator was constructed as follows (see Fig. 3): It consists of a fixed ring-shaped field magnet with magnetic poles projecting inwards and a rotating armature in

the form of a flywheel.[1] This wheel, J (see Fig. 4), was turned down on the edge, forming a kind of flanged pulley, and this groove is wound full of annealed iron wire insulated with shellac. Pins, L, were set in the sides of the ring J, and flat coils, M, of insulated wire wound over the periphery of the armature wheel and around the pins. These coils were connected together in series, and the ends of the series carried through a hollow shaft, H, to slip rings, P, P, from which the currents were taken off by brushes, O, O. The field magnet consisted of a kind of toothed wheel, with the teeth turned inwards (see Figs. 3 and 4), and an insulated wire or strip was wound zigzag fashion between these teeth, so that when a continuous current was passed along this conductor, the teeth were made alternately North and South magnetic poles. It is quite possible thus to produce a magnet having 400 radial poles in the circumference, and also easy

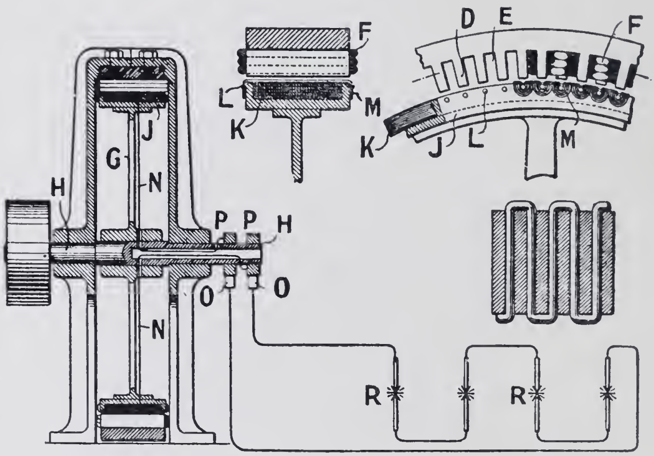


Fig. 4.—Tesla High Frequency Alternator. (*End view.*)

to put 400 coils on the armature. Hence if such a machine is driven at a speed of 3000 revolutions per minute, or 50 per second, it produces an alternating current having a periodicity of 10,000 ~. A machine of this kind can be constructed to give a current of, say, 10 amperes. In the machine above described, which was capable of giving an alternating electromotive force of about 100 volts, the field magnet consisted of a ring of wrought iron 32 inches outside diameter, about 1 inch thick; the inside diameter was about 30 inches. The distance between the teeth was about $\frac{3}{16}$ inch, and each field magnet tooth was about $\frac{3}{16}$ inch thick. On the armature 384 coils were connected in two series. The width of the armature was $1\frac{1}{4}$ inch. With magnetic teeth placed so close it was necessary to have an extremely small clearance between the armature coils and the magnet, to avoid excessive leakage or loss of useful magnetic flux; hence it was impossible to use wire for the armature thicker than

[1] See *The Electrical Engineer* of New York, March 18, 1891, vol. xi. p. 338.

No. 26, Brown and Sharp gauge. This size is equivalent to No. $28\frac{1}{2}$ British S.W.G. The armature wires must be wound with great care, otherwise they are apt to fly off in consequence of the great peripheral speed. It is practicable to run such an armature at a speed of 3000 revolutions per minute, equivalent to a peripheral speed of 375 feet per second.

In another type of machine constructed by Tesla, magnetic leakage was avoided by making adjacent poles on the same side of the armature of the same polarity. In this second form the armature consisted of a copper plate in the form of a disc with a large hole in it see (Figs. 5 and 6). The plate was cut through by radial slits alternately at the inside and outside edge, so as to divide the plate up into a zigzag strip. This plate was clamped on a central boss fixed on a shaft (see Fig. 5), and caused to revolve between the two parts of a field magnet having a large number of inward projecting poles, all those on one side being of the same polarity and facing an equal

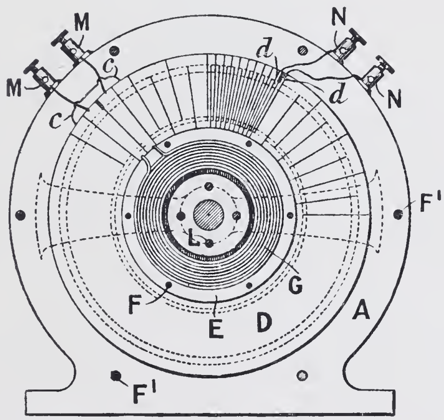


Fig. 5.—Tesla High Frequency Alternator: Disc type. (*Side view.*)

number of like poles on the opposite side, of the opposite polarity (see Fig. 6). In this manner, the disc was perforated by the magnetic flux passing across from one set of poles to another, and the passage of the strips into which the disc is cut up, into and out of these streams of magnetic flux, gives rise to the electromotive force in the armature. The armature winding therefore consisted of a single disc-shaped conductor equivalent to a zigzag winding, and this was driven at a high speed so that the radial elements of the armature cut across streams of magnetic flux. A very strong excitation could therefore be employed without producing any wasteful leakage flux. The essential drawback of this construction is that unless the slits in the armature are very close together, so that the width of the radial bar or slice is not more than $\frac{1}{32}$ inch, there is considerable heating of the armature, due to eddy currents set up in it. In one machine of the last type, constructed by Tesla, the field had 480 polar projections on each side, and from this machine it was possible to obtain a current having a frequency of 15,000 complete periods per second.

When a machine of this description, having a disc of considerable diameter, is driven at a speed of 3000 R.P.M., very accurate balancing is necessary, or otherwise dangerous vibrations will be set up in the machine. Great rigidity and accuracy of work are therefore necessary in all parts of the machine, because the clearance between armature and field magnets must necessarily be very small.

A good plan for obtaining the necessary high relative speed between armature and field without exceeding moderate limits of actual rotation was adopted by Sir David Salomons and Mr. Pyke, who constructed in 1891 a high frequency alternator on the following lines.[2] It consists of two iron discs (see Fig. 7), both having teeth like a crown wheel and each revolving independently on a shaft turning in its own long bearing. The wheels are placed on the ends

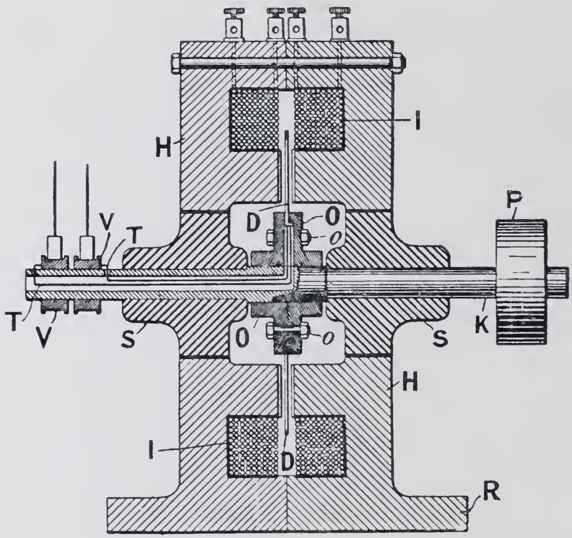


FIG. 6.—Tesla High Frequency Alternator: Mordey or Disc Type. (*Section.*

of the shafts in line with each other so that the projecting teeth are in apposition and can be brought almost into touch with each other by shifting the bearings upon the bed-plate, in grooves made for the purpose of facilitating this adjustment. The discs are each 12 inches in diameter, and one of these discs is so wound as to constitute both the armature of an alternator and the armature of a continuous current motor. With this object, the greater part of the centre of the disc is filled up with a Gramme-wound flat ring armature and the usual commutator, whilst the edge of the disc consists of a large number (about 360) of small iron teeth, round which a fine insulated wire is coiled. These teeth project outwards perpendicularly to the surface of the disc, and by means of insulated slip rings the alternating current can be drawn off from this alternator armature. The

[2] See *Journal of the Institution of Electrical Engineers*, London, 1892, vol. xxi. p. 709.

other disc or wheel constitutes the field magnet both of the alternator and the motor. It has a transverse bar, round which insulated wire is wound forming an electro-magnet, which provides the field for the Gramme armature, and the current also passes in shunt through a wire wound zigzag fashion between projecting teeth on this magnet disc, similar to the winding on the armature disc. A continuous current is supplied to this field magnet by means of a pair of slip rings and brushes, and there is also a brush-holder carrying a pair of brushes fixed to the disc which press against the commutator of the Gramme armature fixed in the other disc. When a continuous current is supplied to the machine at a pressure of 100 volts, it commences to rotate, the two discs running in opposite directions, the continuous current field magnets being pushed backwards as it

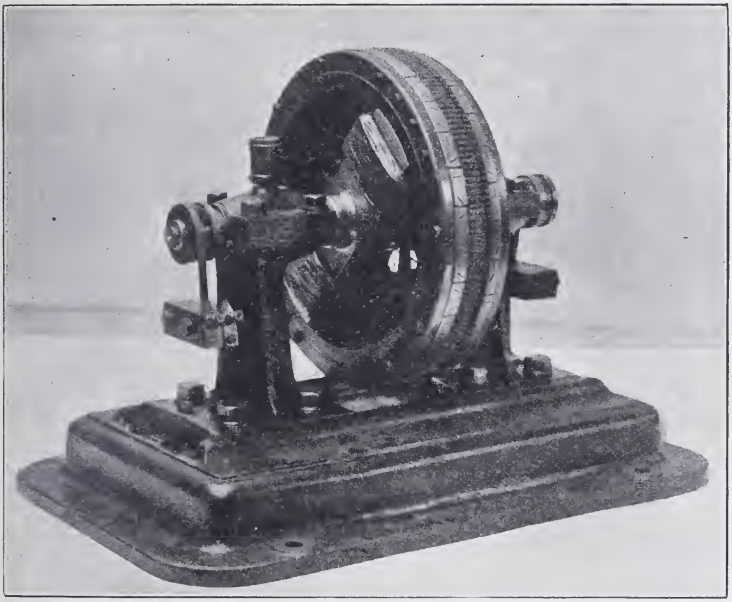


FIG. 7.—Salomons and Pyke High Frequency Alternator.

drives the Gramme armature forwards. In this manner, a differential velocity can be given to the discs equivalent to a speed of 3000 R.P.M. in its effect on the alternating armature. Since there are ten teeth to the inch in the peripheries of the discs and 360 poles in the whole of the circumference, it follows that with an absolute speed of each disc of 1500 R.P.M. an alternating current will be produced in the wire wound in the teeth of the armature disc which will have a frequency equal to 180 times 50, viz. 9000 periods per second.

A description has been given by Mr. B. G. Lamme of a small alternator of 2 K.W. capacity, having a frequency of 10,000. This alternator was built by the Westinghouse Company for Leblanc, who required it for experiments in connection with telephonic research. The alternator is of the inductor type, with 200 polar projections.

The armature was of sheet steel only 3 mils (= 0·003 inch) in thickness. The rotor consisted of a forged steel disc 25 cms. in diameter. Driven at a speed of 3000 R.P.M., the frequency was 10,000 complete periods per second.

Generally speaking, it is not easy to obtain by any of the devices above described a frequency higher than 10,000 periods per second. Very excellent mechanical workmanship and perfect balance are necessary to be able to run any form of disc armature, having a diameter of 30 cms. or so, at a speed of 50 revolutions per second. Such an armature must carry 400 coils to be enabled to give even this frequency.

In consequence of the difficulty of balancing a wound armature, the inductor form of alternator is often adopted for high frequency machines. In this case the revolving part is merely an iron disc having teeth or notches cut on its edge. If two chisel-shaped magnetic poles are placed on either side of such a disc, and if these poles

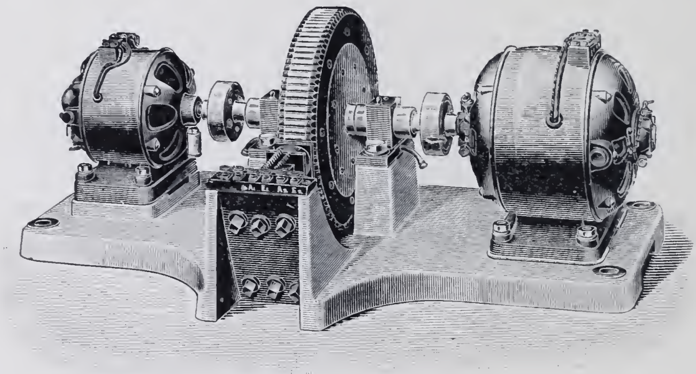


FIG. 8.—Siemens' High Frequency Inductor Alternator.

carry armature coils wound on them, then as the notched iron disc rotates it varies the magnetic reluctance of the magnetic circuit, and hence the flux passing through the armature coils. In Fig. 8 is shown a view of such a high frequency inductor alternator made by Messrs. Siemens Bros., the toothed inductor disc being driven by a motor which also drives on the same shaft a small dynamo which provides the exciting current for the field magnets of the alternator. The frequency and electromotive force are, of course, determined by the speed of this disc. It is easy by it to produce an alternating current of a frequency of 5000.

Mr. W. Duddell has also described the construction of a high frequency alternator of the inductor type.[3] It consists of a laminated soft iron ring having two inwardly projecting poles (see Figs. 9 and 10). This ring is wound with an exciting circuit, so that a direct current flowing in this circuit tends to make one of these poles North and

[3] W. Duddell, "A High Frequency Alternator," *Proceedings of the Physical Society of London*, April, 1905, vol. xix. part v. p. 431.

the other South. In addition, another or armature circuit is laid upon the ring. Between the pole pieces a laminated soft iron disc revolves which has V-shaped notches cut on its periphery.

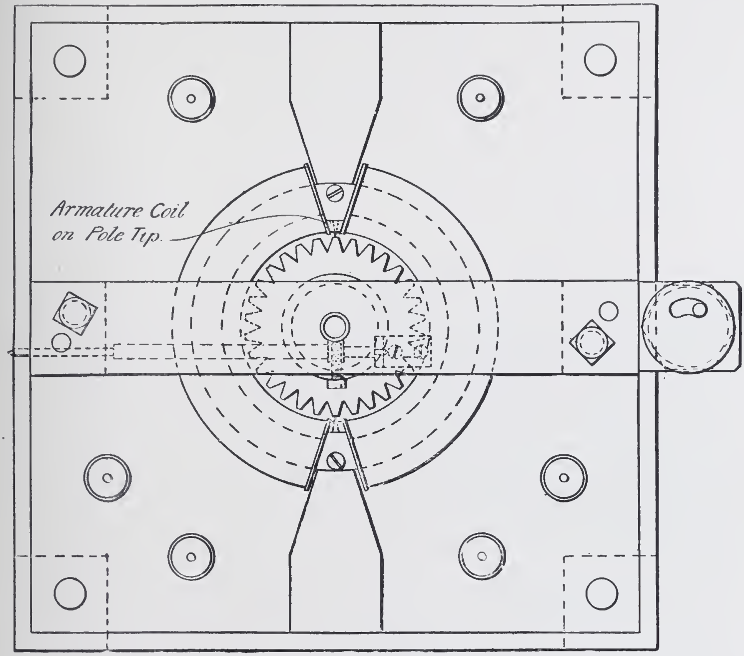


FIG. 9.—Duddell's High Frequency Alternator. (*Plan.*)

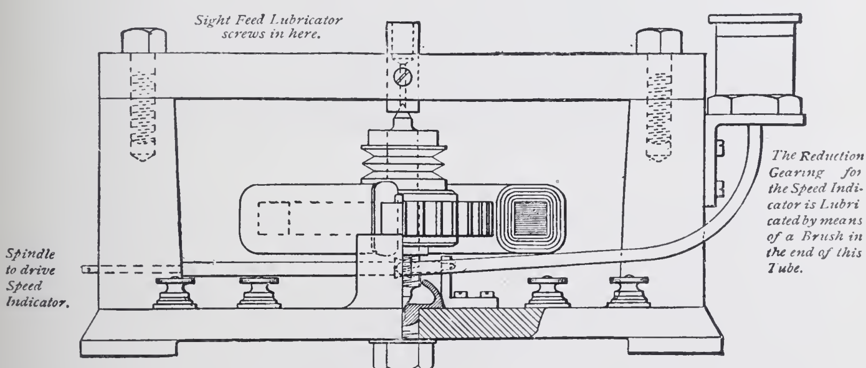


FIG. 10.—Duddell's High Frequency Alternator. (*Elevation.*)

The exciting circuit on the ring had inductance coils inserted in it, so as to prevent high frequency currents being generated in it. The iron inductor disc was revolved by a cotton belt passing round a pulley on the inductor shaft and round two large metal disc pulleys,

which in turn were driven by an electric motor (see Fig. 11). In this manner the inductor disc was driven at 30,000 or 40,000 R.P.M. Alternating currents could be obtained from the armature circuit having a frequency up to 18,000 per second. The machine gave a current (R.M.S.) of 1 ampere and an electromotive force of 40 volts. Subsequently inductors with 50 or 60 teeth were used and driven at speeds up to 600 revolutions per second. This furnished an alternating current having a frequency of 50,000.

Finally an inductor disc was made with 204 teeth, merely a sort of laminated iron disc with a milled edge. Coils of wire were wound on the iron pole tips as armature coils, and with this arrangement it was finally found possible to create an alternating current having a frequency of 120,000 when the disc was driven at a speed of 600

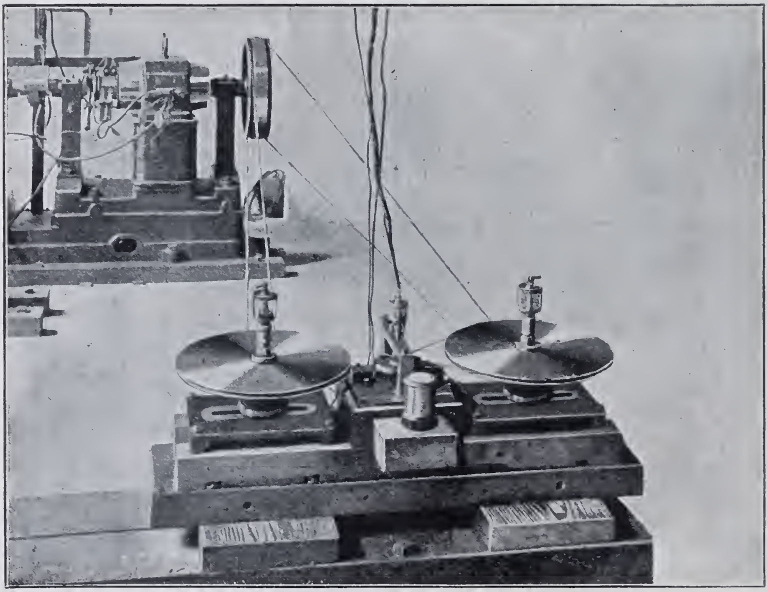
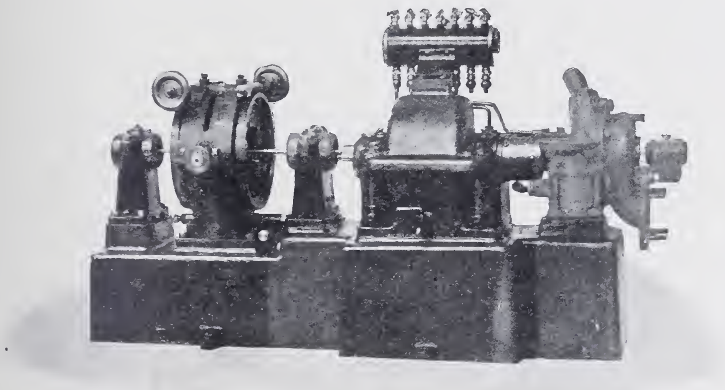


Fig. 11.—Duddell's High Frequency Alternator. (*Perspective view.*)

revolutions per second. On the other hand, the output of the machine was then very small, being only 0·1 ampere at 2 volts. This alternator gave 3·6 volts on open circuit. The machine was constructed for experiments on the electric arc, and not primarily for the purpose of electric oscillation work.

The only inventor who has so far succeeded in constructing high frequency alternators of larger power and higher frequency than those above described is R. A. Fessenden in the United States. Recognizing the difficulties which arise from magnetic leakage when poles of opposite sign are interspaced, he, like Tesla, adopted the Mordey type of alternator, in which the field magnets have poles of the same sign on one side, and the magnet consists of a pair of revolving discs with opposed teeth facing inwards, those on one side

being all N. poles and those on the opposite side S. poles. The fixed armature in the form of a disc is placed between these rows of poles, and in some cases it appears a double armature is employed. The two magnet discs resemble crown wheels with small teeth, between which the wire for carrying the exciting current is wound. One machine thus made by him is said to be capable of giving an alternating current with a frequency of 80,000. In practice it seems to have been limited to 60,000, with an output of 250 watts and an electromotive force of 60 volts when running at a speed of 10,000 R.P.M. At a speed of 8400 R.P.M. it gave a frequency of 50,000 and a voltage of 65. The field magnet of this machine is described as having 360 poles. Another type of alternator coupled direct to a De Laval steam turbine has been constructed and described by Fessenden (see *The Electrician*, vol. 61, p. 441, 1908). De Laval steam turbines are now made in small sizes to run at 30,000 R.P.M. Hence when coupled direct to a shaft running at this speed an



[Reproduced by permission from "The Electrician."

FIG. 12.—Fessenden's High Frequency Turbo-Alternator.

armature of comparatively small diameter will give the required high frequency. In the case of the machine shown in Fig. 12 the alternator gives a current at 225 volts and a frequency of 75,000, with about 2·5 k.w. output. The machine is of the double armature type, with 300 coils on each armature, and a field magnet with 150 teeth. The two air gaps are only $\frac{1}{16}$ inch in length. The steam pressure used with the turbine is 100 lbs. per sq. inch. Fessenden, however, states that he has constructed high frequency alternators having an output of 2 k.w. or more and a frequency of 10,000, and has under construction some giving an output of 20 k.w. and a frequency of 200,000. If such machines can be built at a reasonable price, they will undoubtedly be of very great use in connection with radiotelegraphy and radiotelephony. The great defects of all high frequency alternators so far made are the small output, relatively low frequency, and large terminal voltage drop on taking current from the machine.

In the case of alternators worked at very high speeds on board

ship sudden strains due to gyroscopic action might be brought into play when the ship rolls, unless the alternators are carried on a special form of support.

These alternators in any case cannot have a very high efficiency, because the power expenditure required merely to rotate a disc even of a few inches in diameter at a very high speed is considerable, this power being absorbed in air friction and churning.

The above-named difficulties have deterred all but a few inventors from directing more attention to extra high speed alternators, particularly since the discovery of means for converting a continuous current of electricity into undamped electric oscillations by means of the electric arc. Before, however, we discuss the appliances for the production of undamped oscillations by the last-named method, it will be convenient to consider first the apparatus and methods for the production of damped electric oscillations by means of condenser discharges.

4. Production of Damped Electric Oscillations by the Discharge of a Condenser.—If two conductors receive electrical charges of opposite sign, in other words, are brought to different potentials, and if they are suddenly connected through a conductor having inductance but small resistance, the equalization of their potentials takes place by means of a discharge, consisting of a series of decadent electrical oscillations, or movements of electricity, to and fro along the conductor.

The nature of this phenomenon is best explained by considering a hydrodynamic analogue. Suppose two airtight reservoirs to be connected by a wide pipe having in it a valve which can suddenly be opened. Let one vessel contain air under great pressure, and let the other vessel be exhausted. Then the difference of air pressure between the vessels is analogous to the difference of electric potential of the electric conductors. If then the valve in the pipe is opened, air rushes from the full to the empty vessel, but owing to its inertia it overshoots the mark, and after equalizing the pressure, for an instant reverses the distribution. The air then rebounds, and the pressure is finally equalized only after a series of gradually subsiding to-and-fro movements of air in the pipe have taken place. Each vessel has successively the state of higher and lower pressure, but in decrescent degree.

The conditions for the establishment of such air oscillations between the two vessels are, however, that the pipe be very suddenly opened, and it must offer but little resistance to the movement of the air. If the pipe throttles the air motion, then the pressure would sink gradually in one vessel and rise in the other, but there would be no aërial oscillations. In the same manner, if the equalization of the electrical potentials of the charged conductor takes place through a wire of high resistance, electric oscillations are produced.

We may employ another mechanical illustration of the same effect, as follows :—Suppose a glass U-tube to be partly filled with mercury, and the mercury to be displaced so as to be higher in one limb than the other. There is then a force due to the difference of level urging the fluid to return to an equal height in the two limbs. Let the mercury be allowed to return, but be constrained so that

it is released slowly; it goes back to its original position without oscillations. If, however, the constraint is suddenly removed, then, owing to inertia of the mercury, it overshoots the position of equilibrium and oscillations are created. If the tube is rough in the interior or the liquid viscous, these oscillations will quickly subside, being damped out by friction, but, other things being equal, the denser the liquid the more prolonged will be the time of the oscillations.

The quality we call inertia in material substances corresponds in effect with the inductance of an electric circuit, and the frictional resistance experienced by a liquid in moving in the tube, with the electric resistance of a circuit. If we suppose the U-tube to include air above the mercury, and to be closed up at its ends, the compressibility of the enclosed air would correspond to the electrical capacity in a circuit.

The necessary conditions for the creation of mechanical oscillations in a material system or substance are that there must be a self-recovering displaceability of some kind, and the matter displaced must possess density or inertia. In other words, the thing moved must tend to go back to its original position when the disturbing or restraining force is withdrawn, and must overshoot the position of equilibrium in so doing. Frictional resistance causes decay in the amplitude of the oscillations by dissipating their energy as heat.

In the same way the essential condition for establishing electrical oscillations in a circuit is that it must connect two bodies having electrical capacity with respect to one another, such as the plates of a condenser, and the circuit must itself possess inductance and low resistance. Under these conditions the sudden release of the electrical strain results in the production of an oscillatory electric current in the circuit, provided the resistance of the circuit is less than a certain critical value. We have these conditions present when the two coatings of a charged Leyden jar are connected by a thick copper wire.

Since every charged conductor is merely one coating or surface of a particular type of condenser, it follows that most cases of electric discharge in the form of a spark are oscillatory in character. It is probable that many lightning flashes are oscillatory discharges on a gigantic scale. In a later chapter we shall consider the methods by which the existence of oscillations set up, even when a charged metal ball is discharged to earth by a spark taken by the knuckle, can be demonstrated.

5. General Theory of the Discharge of a Condenser.—It was long ago suggested that the discharge of a Leyden jar does not always consist in the flow of a transient unidirectional current through the discharging circuit, but is in some cases an alternating current diminishing gradually in strength. Joseph Henry, in 1842, came to this conclusion, guided to it no doubt by his observations on the irregular effects attending the magnetization of steel needles by Leyden jar discharges. He remarks [4]—

"The discharge, whatever may be its nature (that is, of a Leyden jar), is not correctly represented by the single transfer of imponderable fluid from one side

[4] "The Scientific Writings of Joseph Henry," vol. i. p. 201. Washington, 1886.

of the jar to the other. The phenomena require us to admit *the existence of a principal discharge in one direction, and then several reflex actions backwards and forwards, each more feeble than the preceding, until equilibrium is obtained.* All the facts are shown to be in accordance with this hypothesis, and a ready explanation is afforded by it of a number of phenomena which are found to be described in the older works on Electricity, but which have until this time remained unexplained."

Von Helmholtz, whose penetrating genius opened up so many new ideas, in his celebrated essay "Die Erhaltung der Kraft" ("The Conservation of Force"), read before the Physical Society of Berlin, July 23, 1847, said—

"We assume that the discharge of a jar is not a simple motion of the electricity in one direction, but a backward-and-forward motion between the coatings, in oscillation which becomes continually smaller until the entire *vis viva* is destroyed by the sum of the resistances."

Lord Kelvin published in 1853 a classical paper, "On Transient Electric Currents,"[5] in which the discharge of the Leyden jar was mathematically treated in a manner which elucidated important facts. He recognized the influence which the "electro-dynamic capacity," or, as we now call it, the *inductance*, of the discharge circuit had upon the effects, and he established an equation of energy which expresses the fact that the energy of the charged jar at any instant is partly being dissipated as heat in the discharging circuit, and partly conserved as current energy in that circuit.

Consider the case of a charged Leyden jar or condenser discharged through a circuit having resistance and inductance. In the act of discharge the electrostatic energy stored up in the condenser is converted into electric current energy and dissipated as heat in the connecting circuit. At any moment the rate of decrease of the energy in the jar is equal to the rate of dissipation of energy in the discharging circuit plus the rate of change of the kinetic or magnetic energy associated with the circuit.

If we confine our consideration of the problem to the limited case in which the discharge current is of such frequency that the motion of electricity in the discharge circuit is at every instant in the same direction in all parts of this circuit, and uniformly distributed over the cross-section of this circuit, we can set out the elementary theory following Lord Kelvin's methods as follows :—

If the capacity of the jar is represented by C, the resistance of the discharge circuit by R, and the inductance of that circuit by L, then an equation of energy may be stated mathematically, as follows :—

$$-\frac{d}{dt}\left[\frac{1}{2}\frac{q^2}{\mathrm{C}}\right] = \frac{d}{dt}\left[\tfrac{1}{2}\mathrm{L}i^2\right] + \mathrm{R}i^2 \quad . \quad . \quad . \quad (5)$$

$$\text{or} \quad \mathrm{L}\frac{di}{dt} + \mathrm{R}i = -\frac{1}{\mathrm{C}}\int i\,dt$$

$$\text{or} \quad \frac{d^2q}{dt^2} + \frac{\mathrm{R}}{\mathrm{L}}\cdot\frac{dq}{dt} + \frac{1}{\mathrm{LC}}q = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$\text{or} \quad TT''\ddot{q} + T'\dot{q} + q = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

[5] "On Transient Electric Currents," by Prof. William Thomson, *Phil. Mag.*, 1853, ser. 4, vol. v. p. 393.

The above equation (5) is merely the symbolical expression of the fact that at any instant the rate of loss of energy by the condenser is equal to the sum of the rate of dissipation of energy in the circuit and the rate of storage of energy in the magnetic field round it.

In equation (7) T' is written for $\frac{L}{R}$ and T'' for CR, whilst $\dot{q}$ and $\ddot{q}$ stand for the first and second time differentials of q.

The above differential equation belongs to a class which occurs in numerous physical investigations, and its solution in the last form consists in finding the value of the quantity of electricity q or the charge of the jar at any instant in terms of the time and the three constants L, R, and C. An equation of this kind has two solutions according to the relation of the constants.

It is easy to show, following Lord Kelvin, that the nature of the solution of the above equation (6) is determined by the relative values of the quantities $\frac{L}{R}$ and LC, or by $\frac{L}{R}$ and $\frac{L}{R}$CR. If $\frac{R^2}{4L^2}$ is greater than $\frac{1}{LC}$, that is, if R is *greater than* $\sqrt{\frac{4L}{C}}$, or if $\frac{RC}{4}$ is greater than $\frac{L}{R}$, the charge in the jar dies away gradually as the time increases, in such a manner that the discharge current is always in one direction.

The ratio $\frac{L}{R}$ is called the *time-constant* (T) of the discharge circuit, and the product CR is called the time-constant (T'') of the condenser circuit. Hence the above condition amounts to saying that the discharge is unidirectional when T is less than $\frac{1}{2}\sqrt{TT''}$, that is, when the time-constant of the inductive circuit is less than half the geometric mean of the time-constants of the inductive circuit and the condenser circuit.

The solution of equation (6) and the determination of these conditions offer no difficulty.

Assume $q = A\epsilon^{mt}$, where A is some constant, ϵ is the base of the Napierian logarithms, and m a quantity to be determined. Then by substitution we have—

$$\frac{d^2q}{dt^2} + \frac{R}{L}\cdot\frac{dq}{dt} + \frac{q}{LC} = q\left(m^2 + \frac{R}{L}m + \frac{1}{LC}\right) = 0$$

$$\text{Hence} \quad m^2 + \frac{R}{L}m + \frac{1}{LC} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Solving the above quadratic equation, we have—

$$m = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

Therefore if $\frac{R^2}{4L^2}$ is greater than $\frac{1}{LC}$, the roots of the quadratic (8) are real, and the solution of (6) takes the form—

$$q = A_1\epsilon^{m_1t} + A_2\epsilon^{m_2t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

In the above equation A_1 and A_2 are constants, and m_1 and m_2 are the two real roots of (8).

If we call Q the total charge of the jar at the instant when the

discharge begins, and reckon the time t from that instant, then when $t = 0$ we have $q = Q$. Also the current i flowing out of the jar $= -\frac{dq}{dt}$, and i is zero when $t = 0$.

Hence from (9), under these conditions, we have—

$$A_1 + A_2 = Q \quad \text{and } A_1 m_1 + A_2 m_2 = 0$$

$$\text{Therefore} \quad A_1 = Q\frac{m_2}{m_2 - m_1} \qquad \text{and } A_2 = -Q\frac{m_1}{m_2 - m_1}$$

Hence the complete solution of equation (6) in the case of the above defined conditions is—

$$q = \frac{Q}{m_2 - m_1}\left(m_2\epsilon^{m_1 t} - m_1\epsilon^{m_2 t}\right) \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$\left.\begin{aligned} \text{where} \quad m_1 &= -\frac{R}{2L} + \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} = -\alpha + \beta \\ \text{and} \quad m_2 &= -\frac{R}{2L} - \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} = -\alpha - \beta \end{aligned}\right\} \quad . \quad (11)$$

The current i at any instant flowing out of the condenser is found by differentiating equation (10) with respect to t.

$$\text{Therefore} \qquad i = -\frac{m_1 m_2 Q}{m_2 - m_1}(\epsilon^{m_1 t} - \epsilon^{m_2 t}) \quad . \quad . \quad . \quad . \quad (12)$$

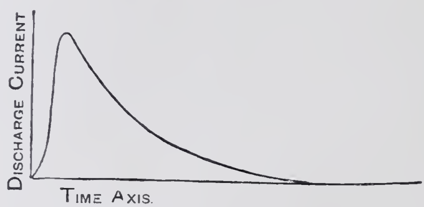


FIG. 13.—Curve representing the Dead-beat Discharge Current of a Condenser.

But when $t = 0$, $i = 0$, and when $t = \infty$, $i = 0$. Hence at some instant the current has a maximum value, and by differentiating equation (12) it is easily found that at a time $t = \frac{\log_\epsilon m_1 - \log_\epsilon m_2}{m_2 - m_1}$, the current i has a maximum value.

Accordingly this result shows us that when the resistance, inductance, and capacity are so related that $\frac{R^2}{4L^2}$ is greater than $\frac{I}{LC}$, or, which is the same thing, when $\frac{CR}{4}$ is *greater than* $\frac{L}{R}$, then the discharge from the condenser is unidirectional, but rises up to a maximum value and then decays (see Fig. 13).

On the other hand, if $\frac{CR}{4}$ is *less than* $\frac{L}{R}$, the roots of the quadratic (8) are unreal, and may be written in the form—

$$\left.\begin{aligned} m_1 &= -a + j\beta \\ m_2 &= -a - j\beta \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

$$\text{where} \quad j = \sqrt{-1},\ \alpha = \frac{R}{2L}, \text{and}\ \beta = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

In this case the solution of (6) is—

$$q = A_1\epsilon^{-(\alpha - j\beta)t} + A_2\epsilon^{-(\alpha + j\beta)t} \quad . \quad . \quad . \quad . \quad (14)$$

Bearing in mind the exponential values of the sine and cosine, viz.—

$$\sin\theta = \frac{\epsilon^{j\theta} - \epsilon^{-j\theta}}{2j}, \quad \cos\theta = \frac{\epsilon^{j\theta} + \epsilon^{-j\theta}}{2}$$

we can write equation (14) in the form—

$$q = \epsilon^{-\alpha t}\left\{(A_1 + A_2)\cos\beta t + j(A_1 - A_2)\sin\beta t\right\}$$

Hence from the values of A_1 and A_2 already obtained we arrive at the equation—

$$q = \frac{Q\epsilon^{-\alpha t}}{m_2 - m_1}\left\{(m_2 - m_1)\cos\beta t + j(m_2 + m_1)\sin\beta t\right\}. \quad (15)$$

as an expression for q.

Therefore since the discharge current $i = -\frac{dq}{dt}$, we have by differentiation of (15)—

$$i = \frac{Q\epsilon^{-\alpha t}}{m_2 - m_1}\left\{(m_2 - m_1)(\alpha\cos\beta t + \beta\sin\beta t) + j(m_1 + m_2)(\alpha\sin\beta t - \beta\cos\beta t)\right\}$$

and from the values for m_1 and m_2 given above we have finally—

$$i = Q\epsilon^{-\alpha t}\left(\frac{\alpha^2 + \beta^2}{\beta}\right)\sin\beta t \quad . \quad . \quad . \quad . \quad (16)$$

If in equation (15) we substitute the values of m_1 and m_2 given in equation (13), we have—

$$q = Q\epsilon^{-\alpha t}\left(\cos\beta t + \frac{\alpha}{\beta}\sin\beta t\right)$$

Also if v is the potential difference of the plates of the condenser at the time t, and V their initial potential difference, $Q = CV$ and $q = Cv$, where C is the capacity. Hence—

$$v = V\epsilon^{-\alpha t}\left(\cos\beta t + \frac{\alpha}{\beta}\sin\beta t\right)$$

In all practical cases of oscillatory circuits the ratio $\frac{\alpha}{\beta}$ is small compared with unity, and then $\beta = \frac{1}{\sqrt{LC}}$. Lower down (see equation (20)) this last quantity β is shown to be equal to $2\pi n = p$, when $R = 0$ or $\alpha = 0$. Hence under these conditions the above equation and also equation (16) take the form—

$$\left.\begin{aligned} v &= V\epsilon^{-\alpha t}\cos pt \\ i &= CpV\epsilon^{-\alpha t}\sin pt \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

These last equations are of the same form as the expression $i = I\epsilon^{-\alpha t}\sin pt$ given on page 4 as the equation for the wavy line obtained by the projection of the point moving along a logarithmic

spiral. They show, therefore, that both the currents in the circuit and the potential difference of the condenser plates decay in accordance with the law of a damped oscillation train.

It is necessary, however, to call attention at this point to the fact that when circuits are traversed by high frequency currents the resistance R and the inductance L of the discharge circuit which make their appearance in the above equations have not the same numerical values as the resistance and inductance involved when steady continuous currents are passing through the circuit. Accordingly, the above statements as to the condition under which the oscillatory form of discharge is produced are subject to a certain correction, but, broadly speaking, we may say that when the resistance of the discharge circuit is very low the discharge will take the oscillatory form.[6] If we examine the equation (16) for the discharge

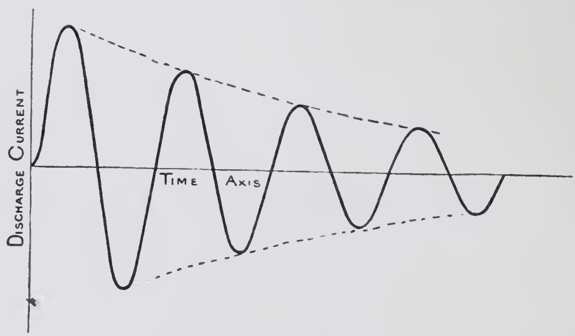


Fig. 14.—Curve representing the Damped Oscillatory Discharge Current of a Condenser.

current, we see that it shows that the current is zero at intervals of time corresponding to $\sin \beta t = 0$. It follows that these times of zero current are therefore spaced out at equal intervals, each equal to $\frac{\pi}{\beta}$. Also the maximum values of the currents in either direction decay away in geometric progression as the times increase in arithmetic progression. The discharge current in the two cases, viz. the *dead-beat* case and the *oscillatory* case, corresponding to the equations (12) and (16), can therefore be represented graphically by the two curves shown in Fig. 13 and Fig. 14.

The ordinates of the curve in Fig. 13 represent the discharge current at various instants during the discharge in the dead-beat or non-oscillatory case, and the ordinates of the curve in Fig. 14, the currents in the oscillatory case. In this last, the ordinates above the

[6] See sections 1 and 2, Chap. II., of this treatise. When the frequency is so low that the discharge current is uniformly distributed over the cross-section of the conductor, or when the conductor is so laminated that this is the case, the quantity R in the equations above is the ordinary or ohmic resistance and L is the ordinary inductance, but when the frequency is so high that the current is not so distributed, then the resistance R and inductance L must be replaced by the high frequency resistance and inductance of the circuit.

datum line represent currents in one direction, and those below, currents in the opposite direction. The gradual decrease of the maximum ordinates indicates the damping.

The Napierian logarithm of the ratio of any maximum current or ordinate to the next maximum in the opposite direction multiplied by twice the frequency, gives us the value of the damping coefficient α as shown in section 2. Accordingly, we have, $\alpha = \frac{R}{2L} = 2n\delta$, and $\beta = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$. Taking $\frac{T}{2}$ to represent the interval of time between two successive values of zero discharge current, when it is oscillatory, we see from the above that—

$$T = \frac{2\pi}{\beta} = \frac{2\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Hence the oscillations are isochronous, and their frequency $n = \frac{1}{T}$, is given by—

$$n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

If R is so small that $\frac{R^2}{4L^2}$ can be neglected in comparison with $\frac{1}{LC}$, then the frequency is given by the expression—

$$n = \frac{1}{2\pi\sqrt{LC}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

In this equation (20) the quantities C and L must be measured in homologous units when the expression is employed in practical calculations. That is to say, C and L must both be expressed or measured in electromagnetic units or both in electrostatic units or else in practical units, viz. in *farads* and *henrys*.

In the majority of cases with which we are concerned in radiotelegraphy the resistance of the oscillatory circuit is negligible, the capacity is small, and conveniently measured in *microfarads* or fractions of a microfarad, and the inductance is best expressed in absolute C.G.S. electromagnetic units, viz. in *centimetres*.

Bearing in mind that a microfarad is 10^{-6} of a farad, or 10^{-15} of an absolute electromagnetic unit of capacity, we can convert the above formula (20) for the frequency n into the form

$$n = \frac{5{\cdot}033 \times 10^6}{\sqrt{\text{capacity in microfarads} \times \text{inductance in centimetres}}} . \quad (21)$$

The constant 5·033 is the value of $\frac{\sqrt{1000}}{2\pi}$, which is required in the transformation of the units, and in practice may be taken as equal to 5. We shall frequently have occasion to make use of the above formula in practical calculations.

6. Experimental Confirmation of Theory—The Objective Representation of Electric Oscillations.—The predictions of Lord

Kelvin and Von Helmhotz, that the discharge of a condenser may take place by a series of electric oscillations or alternating and decadent discharges, subsequently received abundant experimental confirmation.

The first to give this confirmation was B. W. Feddersen, who, in 1858 and 1859, published an account of his experiments on the examination of the spark of a Leyden jar by the aid of a rapidly revolving mirror (see *Poggendorff's Annalen der Chemie und Physik*, vol. 103, p. 69). Feddersen found that the image of the spark was not always drawn out into a uniform band of light when viewed by reflection in a rapidly revolving mirror, but when the resistance of the discharge circuit was low, this image was seen to be composed of a number of separated images, thus proving the existence of separate discharges or oscillations.

Paalzow also described, in 1861 and 1863, experiments with a vacuum tube, which proved that these intermittent discharges of a

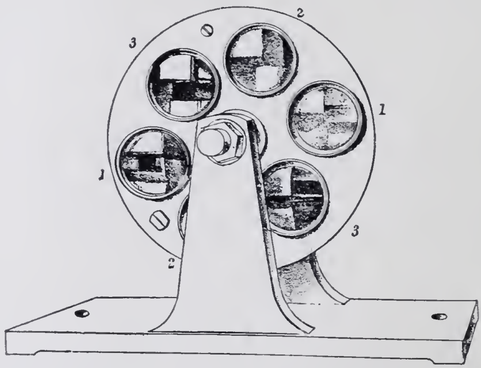


FIG. 15.—Prof. Boys' Revolving Lens Disc for Photographing Oscillatory Electric Sparks.

Leyden jar are alternately in opposite directions. He passed the discharge, or a part of it, through a vacuum tube, and found that if the discharge circuit had a high resistance, the difference in the appearance of the glow at the two electrodes showed that the discharge was unidirectional. If, however, the resistance of the discharge circuit was low, then the identity in appearance showed that the discharge was bidirectional. Moreover, a magnet held near the tube then split the discharge into two lines of light, thus proving that the discharge was alternating (see *Poggendorff's Annalen der Chemie und Physik*, vol. 112, p. 567, and vol. 118, p. 178).

Many years later, Vernon Boys photographed the oscillatory spark of a Leyden jar by another ingenious method. He employed a series of lenses set in a rapidly revolving disc (see Fig. 15).[7] These lenses projected upon a photographic plate images of the spark of the jar. The lenses were set at various distances from the centre of the disc so that each lens formed its own separate curved image of the spark, which was circular in form.

[7] See Vernon Boys, *Proc. Phys. Soc. Lond.*, November, 1890, vol. xi. p. 1.

The Leyden jar was replaced in some experiments by a condenser formed of a number of sheets of window glass with metal plates or coatings placed between, and was connected in series with a large inductance, so as to give to the circuit a somewhat low natural frequency.

The capacity of the condenser was measured, and the inductance also predetermined. The capacity used was about 0·1 of a microfarad. The inductance consisted of a large coil of insulated wire having an inductance of 0 026 of a henry. Hence the oscillation frequency was about 3300. The several images of the spark were projected by the revolving lenses upon a photographic plate and drawn out into segmental bands, broken up into dark and bright portions, corresponding to the electric oscillations. From the known

Fig. 16.—Photograph of an Oscillatory Electric Spark taken by Prof. Boys with a Revolving Lens.

speed of the lens disc, the time interval corresponding to each separate spark image could be calculated. One of the photographs is shown in Fig. 16. The photographs showed from 14 to 23 oscillations per spark, and the measured periodic time or frequency agreed very well with that calculated from the inductance and capacity.

Professor J. Trowbridge has also obtained some interesting photographs of oscillatory sparks taken from the discharge of a large glass plate condenser charged by means of a battery of 20,000 small lead storage cells. The battery was employed to charge the condenser plates in parallel, and then these last were changed by a commutator into series so as to add up the potentials. In this manner he obtained discharges representing a potential difference of 3 million volts.[8] The

[8] See a paper read by Professor J. Trowbridge at a meeting of the American Academy of Arts and Sciences, Harvard University, Cambridge, U.S.A., or *Nature*, August 2, 1900, vol. 62, p. 325, "On some Results obtained with a Storage Battery of Twenty Thousand Cells."

sparks were 6 or 7 feet in length, and photographs of them showed distinctly their oscillatory character (see Fig. 17).

By using a large inductance, the frequency was reduced as low as 800. The frequency of the oscillatory spark represented in Fig. 17 is 5000.

Trowbridge found that with potentials of 3 million volts air at ordinary pressures became conducting, and he also showed by photographs that the discharges through air at this potential resembled miniature flashes of lightning, and were clearly oscillatory in character.

Professor Trowbridge has also given in another place some beautiful reproductions of photographs of oscillatory sparks.[9] In these experiments a condenser was charged by an induction coil actuated by an alternator, and the discharge took place across a spark gap in a primary coil or circuit having inductance. This circuit acted inductively upon the two other circuits, also having inductance and capacity in them, and each also having a spark gap.

The images of sparks occurring at the three spark gaps were simul-

FIG. 17.—Photograph of Oscillatory Electric Sparks, taken by Prof. Trowbridge.

taneously photographed by being thrown on a sensitive plate after reflection from a revolving mirror. The spark images were therefore drawn out into bands of light (see Fig. 18), and these were serrated at the edges when the spark was oscillatory.

These researches clearly showed that even when the primary spark was not oscillatory it could yet give rise to an oscillatory secondary current in one of the adjacent circuits.

Another matter studied by Professor Trowbridge was the influence of the magnetic permeability of the material in and near the discharge circuit.

If the inductance coil through which the condenser discharge takes place has an iron core inserted into it, the resulting increase of inductance shows itself by the reduction in frequency of the oscillatory spark. Also since the magnetic hysteresis of the iron demands an energy expenditure, this damps out the oscillations more quickly than would otherwise be the case. This is well indicated by some photographs of oscillatory sparks taken by Dr. E. W. Marchant in Lord Blythswood's laboratory at Renfrew. He photographed, by the aid of a revolving mirror, the oscillatory spark obtained by discharging a condenser formed of glass plates coated with tinfoil. The condenser had a capacity of 0·06 microfarad, and the resistance coil through which it was discharged an inductance of 0·005 henry. The frequency was

[9] See *Phil. Mag.*, August, 1894, ser. 5, vol. 38, p. 182, Plate VII.

therefore about 9000. The condenser was charged to 13,500 volts. The image of the spark in the revolving mirror is shown in Fig. 19.

A core of 550 iron wires No. 28 S.W.G. was then inserted in the inductance coil, and the spark again photographed. In this last case the frequency of the oscillations, as shown by the time-interval between the successive images, is markedly decreased (see Fig. 20). Also the decay of the oscillations is seen to be increased, thus showing the augmented damping due to the iron core.[10]

If the oscillations do not exceed a certain frequency, one of the simplest methods of photographing them and comparing the observed frequency with that calculated from the capacity and inductance, is the method adopted by Dr. A. Schuster and Dr. G. A. Hemsalech.[11]

In this case a circular sheet of photographic sensitive film is attached to the flat surface of a steel disc which revolves inside a closed box. The disc is capable of revolving at a speed of 120 turns per second, and as it has a diameter of about 33 cms., a point near the edge has a linear velocity of about 10,000 cms. per second, or 100,000 mms. per second. The box in which the disc is contained has a small slit opposite the periphery of the disc, and by means of a lens an image of another slit, illuminated by an electric spark behind it, can be thrown upon the sensitive film. When the spark is continuous, the photographic image on the film is a band of light, the length of which corresponds with the duration of the spark, but when

FIG. 18.—Photographs of Oscillatory Electric Sparks by Prof. Trowbridge, taken with a Revolving Mirror.

[10] See a letter by Dr. E. W. Marchant, *Nature*, vol. 62, p. 413, August 30, 1900.

[11] See G. A. Hemsalech, *Journal de Physique*, February, 1902, "La Constitution de l'étincelle électrique."

the spark is oscillatory, the image is a series of separated images. As 1 mm. between the images corresponds to about 0·00001 of a second, we can determine from the angular separation of the images and the speed of the disc the frequency of the oscillations. In Fig. 22 is shown a photograph of the oscillatory spark taken by Dr. Hemsalech by this means. Fig. 21 shows the image on the plate when the disc is at rest, and Fig. 22 shows the image of the oscillatory spark produced when a condenser consisting of eight large Leyden jars

Fig. 19.—Coil without Iron Core. Fig. 20.—Coil with Iron Core.
Photographs of Oscillatory Electric Sparks, taken with a Revolving Mirror by Prof. Marchant.

(capacity about 0·048 mfd.) was discharged through an inductance of 0·042 henry or 42,000,000 cms.[12]

The frequency is therefore about 3500 complete periods per second.

If the bobbin forming the inductance had an iron core 18 mms. in diameter inserted into it, the effect was to greatly reduce the number of oscillations in the train (see Fig. 23). This photograph shows clearly that the iron core absorbs some of the energy of the discharge and acts as an additional damping. As already stated, this is due to the magnetic hysteresis loss and to the energy loss due to the eddy electric currents set up in the core by the rapid oscillatory magnetization to which it is subjected. These photographs are interesting

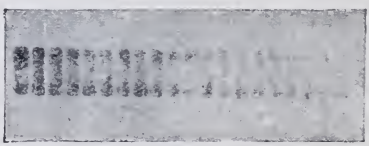


Fig. 21. Fig. 22. Fig. 23.
Photographs of an Oscillatory Electric Spark, by Dr. Hemsalech.

because they reveal to us something of the mechanism of the discharge. By examining the image of the spark with a spectroscope, Dr. Schuster and Dr. Hemsalech have shown that in this case the first effect of the initial oscillation is to pierce the air between the discharge balls, or rather that the electric current constituting the first oscillation is carried by conduction through the air of the spark gap. This forms the so-called "pilot spark," which is well shown in certain photographs. The energy of this first oscillation volatilizes some of the metal of the spark balls and creates a supply of metallic vapour, which conducts the next oscillation, and thereafter each oscillation

[12] See A. Schuster and G. A. Hemsalech, *Phil. Trans. Roy. Soc.*, 1899, vol. 193, p. 189. Also G. A. Hemsalech, *Comptes Rendus*, 1901, vol. 130, p. 898; vol. 132, p. 917.

travels in or by the conducting metallic vapour produced by the preceding oscillation, and in turn creates a further supply. Hence the energy of the oscillatory discharge is chiefly expended in creating the metallic vapour between the electrodes whereby the discharge passes. Interesting questions therefore arise as to the resistance of the electric spark, and whether this resistance remains constant during the whole period of a train of oscillations. We shall return to the consideration of this matter in connection with the damping of electrical oscillations in circuits containing a spark gap.[13] Meanwhile it is sufficient to say that the resistance of an oscillatory spark as used in wireless telegraphy is rarely more than a fraction of an ohm. It does not remain constant during the discharge, but increases towards the end of each train of oscillations. Generally speaking, it may be said that the larger the quantity of electricity which passes at each oscillation, the less is the equivalent spark resistance.

It is found, however, that the equivalent resistance of a single spark or single isolated group of oscillations is different, and greater than that of a closely recurring series of oscillatory electric discharges.

Whilst the above-described methods enable us to photograph and thus analyze an oscillatory discharge, there are other processes which enable us to observe visually the oscillations which compose the train, or at least some optical effects equivalent to them. Four such methods are known and used, viz. those depending on the use of an oscillograph, a Braun cathode ray tube, a Gehrcke oscillographic vacuum tube, and lastly a method which depends upon the effects of an air blast upon an oscillatory spark.

The first of these methods with the oscillograph is only suitable for the objective representation of or for photographing oscillations of relatively low frequency, say, a few hundreds up to 1000 or 1200 per second.

An oscillograph is a type of galvanometer in which the movable part of the instrument, whether coil or needle, which is displaced when a current flows through it has such a high natural time period of its own, from $\frac{1}{2000}$ to $\frac{1}{10000}$ of a second, that it can follow consecutively the fluctuations in the value of a periodic current passing through the instrument, when these are not too rapid.

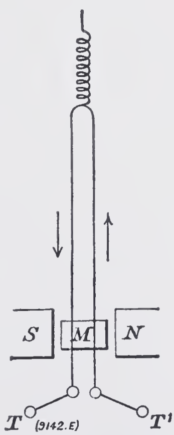


Fig. 24.—Diagram of Duddell Oscillograph.

In one form as constructed by Duddell, it consists of a loop of fine wire (see Fig. 24) placed in a strong magnetic field having a small mirror, M, resting on the two wires forming the loop. A ray of light from an arc lamp falls on this mirror, and is then again reflected from a larger mirror on to a screen or photographic film. When an alternating current is passed through the loop of wire, the two sides of the loop vibrate so that the attached mirror oscillates synchronously about a vertical axis. The second mirror is made to oscillate by a small motor synchronously about a horizontal axis, and the combined motions cause the ray of light to

[13] See Chap. III. of this treatise.

possess a double motion and to delineate on the screen a curve which reproduces the wave form of the alternating current in the wire loop of the oscillograph.

To adapt this appliance to delineate the discharge of a condenser, the author fixed on the shaft of an alternator a disc of insulating material, having on its edge brass sectors. Against this disc three brass wire brushes press, and the sectors are so arranged that as the disc revolves the middle brush is alternately connected first to one and then to the other of the outside brushes. If, then, a condenser, battery, and oscillograph loop are joined up as shown in Fig. 25, it will be evident that as the disc revolves the condenser is alternately charged by the battery and discharged through the oscillograph. The number of sectors on the disc is made the same as the number of pairs of magnetic field poles of the alternator. The small synchronous motor of the oscillograph is then driven by the current of the alternator. Hence the ray of light reflected on to the screen

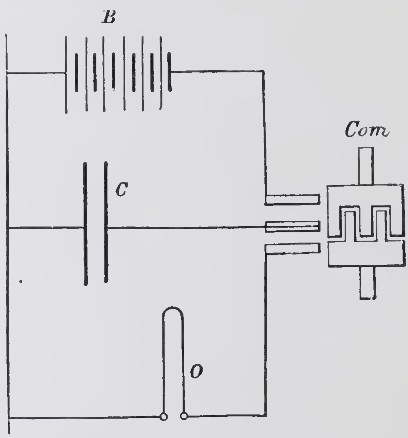


Fig. 25.—Arrangement of Condenser, *C*; Commutator, *Com.*; battery, *B*; and oscillograph, *O*, for delineating Condenser Discharge Curves.

of the oscillograph continually repeats the same motion, and a naturally non-repetitive process, like the discharge of a condenser, is made periodic, and therefore suitable for record by the oscillograph.

Photographs can then be taken showing the variation of the condenser discharge current for various capacities, inductances, and resistances in the discharge circuit. In the Pender Electrical Laboratory, University College, London, a number of such discharge curves were photographed, using a paraffin paper condenser of capacity variable between 0·5 and 7·0 mfds., an inductance consisting of a long helix of copper wire of 31·5 millihenrys ($= 31{\cdot}5 \times 10^6$ cms.), and added non-inductive resistances of various values. The curves given in Plate I., Figs. 1 to 5 (see p. 110), are reproductions of these photographs. Curves 1 to 5, inclusive, are the discharge curves of various capacities from 7·0 to 0·75 mfd. through an inductance always equal to 31·5 millihenrys. In curves 6 to 10, inclusive, a capacity of 0·5 mfd. had non-inductive resistances varying

from 0 to 52·4 ohms added in series with it and with the inductance coil, which itself had a resistance of 7 ohms and inductance of 31·5 millihenrys.

The time period of oscillation was measured on the photographic plate, and calculated in fractions of a second from the observed speed of rotation of the alternator. This time period is given on the diagrams by the numerical value denoted by "T measured." The calculated time period, denoted on the diagrams by "T calculated," is obtained from the Kelvin formula $T = 2\pi\sqrt{CL}$, and the known values of the capacity and inductance used in each case. It will be seen that in every case "T calculated" agrees very well with "T measured."

As a further confirmation of the accuracy of this fundamental formula, the values of the measured time periods of oscillation in each case were then set out in the form of a curve (see Fig. 26) in

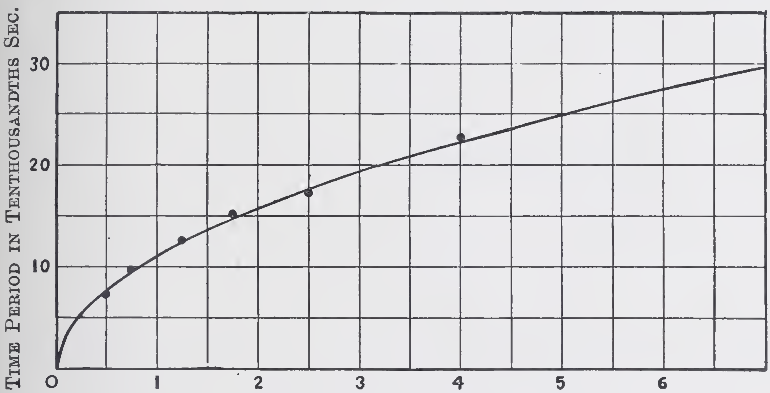


FIG. 26.

terms of the capacity used. The points of observation were found to lie closely on a parabola, showing that the square of the time period varies very exactly as the capacity, as it should do by the Kelvin formula.

These photographs show in a striking manner the way in which the time period increases with the capacity. They also show how the introduction of resistance into the circuit damps out the oscillations. It should be noted that in all but the last two photographs the time interval allowed by the commutator for the discharge was not sufficient to take in all or nearly all the oscillations which would have taken place if circumstances had permitted.[14]

Another method of objective representation is found in the use of

[14] Some excellent photographic curves representing the damped oscillations of condenser discharges have also been taken by Prof. E. Taylor Jones with a short-period electrometer used for determining the frequencies of slow electrical oscillations (see *Phil. Mag.*, vol. 14, 6th series, August, 1907, p. 238). The experimental results obtained by Prof Taylor Jones also agree with the Kelvin formula with considerable exactness. These are referred to in § 11, Chap. III.

a Braun cathode ray tube.[15] This tube is a form of high vacuum tube, having at one end a cathode from which cathode rays are projected (see Fig. 27). The tube T has in it two baffle screens with small holes in them, and on an enlarged anticathode end a screen, B, of phosphorescent material. When the tube is set in operation by a large electrostatic electrical machine, such as a Voss or Wimshurst, giving a unidirectional and continuous discharge, so that a continuous projection of cathode particles takes place from the cathode, we see on the screen a brilliant point of light due to the cathode ray phosphorescence. This ray is a flexible conductor. If, then, a pair of coils traversed by an electric oscillation are placed on either side of the neck of the tube, the cathode ray is deflected up and down by the alternating magnetic field of the coils, and the spot of light on the screen is expanded into a line of light. If this line of light is examined in a rotating mirror suitably placed, it can be expanded into a wavy decrescent line of the form of the lines in the photographs taken with the oscillograph. Although the plan succeeds in producing an objective representation of the discharge current, it is

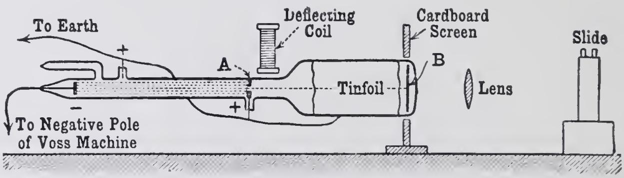


Fig. 27.—Method of employing a Braun Cathode Ray Tube to delineate Alternating Current Curves.

more troublesome to operate, and not so suitable for quantitative work as the method employing the oscillograph above described.

Professor F. Braun and Dr. J. Zenneck have pointed out that such a tube may be used to trace the forms of alternating current curves (see *Annalen der Physik*, 1902, vol. 9, p. 497); and Dr. W. Mansergh Varley has described the use of it in high frequency work.[16]

The arrangement used in connection with the Braun tube for delineating alternating current curves is shown in Fig. 27. For the optical delineation of oscillatory discharges, Messrs. Varley and Murdoch recommend an electrostatic method of deflecting the cathode ray. In Fig. 28 a diagrammatic scheme of the apparatus is shown. The Braun tube T has its cathode terminal led to the negative pole of a Voss machine driven by a small electric motor. Two brass plates, P, P (see Fig. 28), are placed on either side of the tube just beyond the diaphragm in it, and these are connected with the spark balls of the oscillatory circuit containing a condenser, K, and an inductance, L. The plates P, P were about $3\frac{1}{4}$ inches by $2\frac{1}{4}$ inches in size, and placed 3 inches apart. The capacity was 0·003 mfd., and the inductance about 1 henry, being the secondary circuit

[15] See Prof. F. Braun, *Wied. Ann. der Physik*, 1897, vol. 60, p. 552.

[16] See Dr. J. Mansergh Varley, *Phil. Mag.*, 1902, ser. 6, vol. 3, p. 500; and also Dr. Varley and Mr. W. H. F. Murdoch, *The Electrician*, 1905, vol. 55, p. 335, on "Some Applications of the Braun Cathode Ray Tube."

of a small transformer. On the phosphorescent screen B is seen a brilliant green spot of light when the cathode tube is in action, and this expands into a bright line when the condenser discharges take place, since the electrostatic field then produced between the plates P, P deflects the cathode ray up and down. If this line of light is examined in a revolving mirror, the usual form of discharge curve of a condenser is seen in it. In carrying out this experiment, the widened part of the cathode tube should be covered with tinfoil and earthed. An interesting set of experiments was carried out in 1895 by Professor A. Hay, in which the discharge curve of a condenser was graphically delineated by a modification of the Joubert point-by-point method so much used in connection with alternating currents. For the details of these experiments, the reader is referred to the original paper in *The Electrician*, 1895, vol. 35, p. 840. The results confirmed experimentally the predictions of the theoretical formula for the frequency and strength of the discharge at various instants.

A very beautiful method of rendering the oscillations in an oscilla-

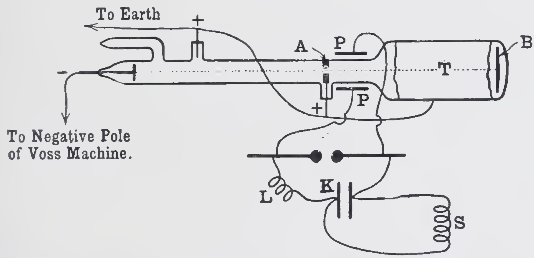


FIG. 28.—Method of employing the Braun Cathode Ray Tube with Electrostatic Deflection plates for delineating Condenser Discharge Curves.

tory spark visible has been employed by Lehmann, Klingelfuss,[17] Zehnder,[18] and Hemsalech.[19] Hemsalech's method has the great advantage of rendering the oscillations visible to the eye, whilst at the same time they can be photographed if necessary. The method is as follows:—

Two plates of thick copper, A and B (see Fig. 29), about 8 mm. in thickness, 8 or 10 cms. in length, and 4 or 5 cms. in width, have one pair of edges bevelled off, and these edges are set at a slight angle to one another. On the top of these plates are fixed two screws, *a* and *b*, by means of which are clamped two short thick platinum wires, the points of which project very slightly beyond the edges of the copper. Above this is fixed a glass tube through which a powerful blast of air can be forced, the diameter of the jet being 3 mm. and the interval between the platinum points 3 or 4 mm. The jet of air should issue with the velocity of about 36 metres per second. The two plates are connected through an inductance, S, and a condenser, C (see Fig. 30), and with an induction coil which

[17] Klingelfuss, *Ann. der Physik*, 1901, vol. v. p. 837.
[18] L. Zehnder, *Ann. der Physik*, 1902, vol. ix. p. 899.
[19] G. Hemsalech, *Comptes Rendus*, 1903, vol. 140, p. 1103.

can make an oscillatory discharge across the platinum points connected with the two copper plates A and B. If the air blast is set in operation, then when the induction coil is set working it charges the condenser, which is discharged across the spark gap intermittently. This intermittent spark is an oscillatory discharge, but the

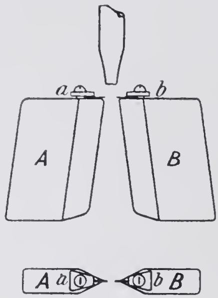


Fig. 29.

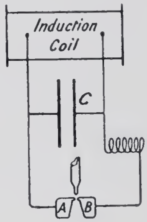


Fig. 30.

Figs. 29, 30, 31, and 32 are, by kind permission of Dr. Hemsalech and M. Ch. Delagrave, taken from "La Science au XXe Siècle."

oscillations are of course superimposed. When the air blast is started, the successive oscillatory discharges are separated from one another and move down between the edges of the copper plates, each successive discharge being represented by a bright band in the shape of an arrow-head, and the whole series of oscillations constitute one train, forming a band traversed with V-shaped bars of

Fig. 31.

Fig. 32.

Photographs of Oscillatory Discharges taken by Dr. Hemsalech.

light, one below the other (see Figs. 31 and 32). This spectrum can be photographed and also observed by the eye. The method has the great advantage that we can observe the effect of varying the different factors in the discharge circuit. Thus, for instance, the introduction of any source of energy absorption into the circuit, such

as the insertion of iron wires into the inductance coil, causes a diminution of the number of oscillations in a train, and therefore shortens the spectrum; and in the same way anything which causes the absorption of energy in the condenser produces an immediate effect upon the appearance of this drawn-out discharge. The method is particularly applicable for lecture illustration.

Another most valuable method of obtaining an objective repre-

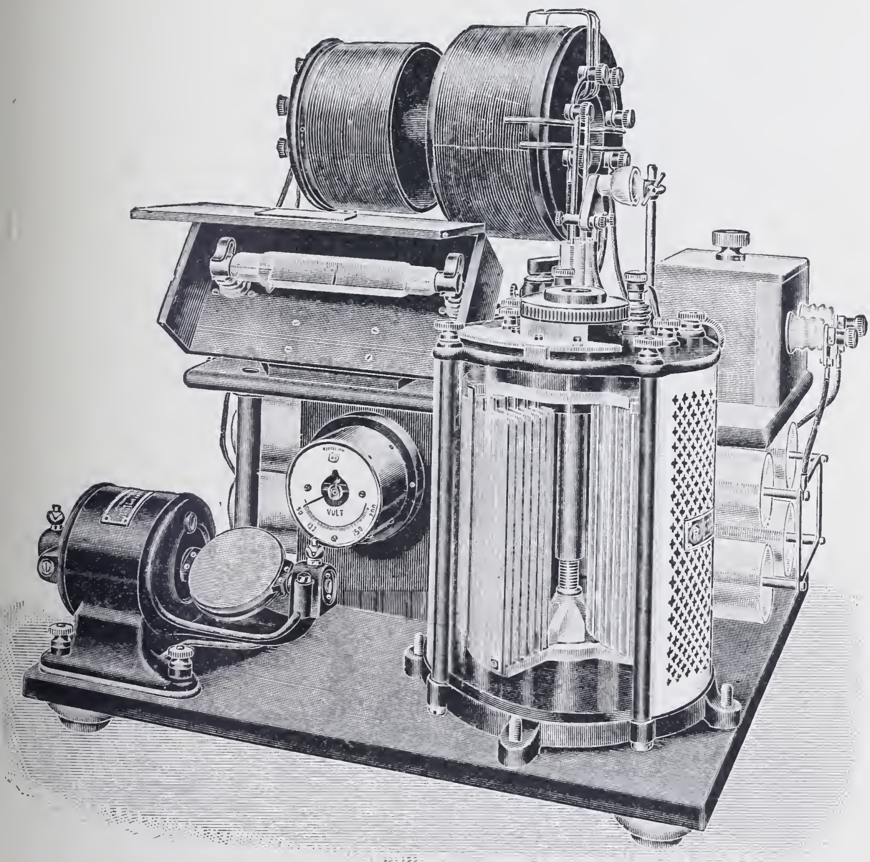


FIG. 33.—Apparatus for using the Gehrcke Oscillograph Tube for Photographing Electric Oscillations. (Hans Boas.)

sentation of electric oscillations is by the use of an oscillograph vacuum tube invented by Dr. Gehrcke. This consists of a glass tube having in it two polished aluminium strips or wires (see Fig. 33), the strips being about 10 cms. long and 15 mm. wide, fixed to a platinum wire sealed through the glass and nearly meeting in the middle of the tube. The tube is exhausted of its air and then filled with nitrogen under a pressure of 8 mm. Under these circumstances,

if a sufficiently large difference of potential is made between the electrodes, the glow light extends over both electrodes for certain distances proportional to their difference of potential. When such a tube is connected to the terminals of a condenser which is creating an oscillatory discharge, the length of the glow light on the aluminium strips or wires varies with every change of potential of the condenser terminals. If, then, the tube is examined in a revolving mirror, the successive images are separated out from one another into a number of bars of light, decreasing successively in length if it is a damped oscillation, or maintaining a uniform length if it is an undamped oscillation. The diagrams in Fig. 34 are from photographs thus taken by Herr Hans Boas of a damped electric oscillation.

A modification of the tube, in which there are two anodes and one cathode, enables two photographs to be taken simultaneously. To observe the oscillations it is, of course, necessary to employ a

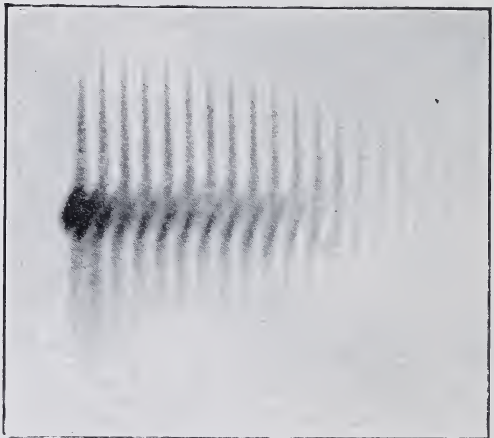


Fig. 34.—Photograph of a Damped Electric Oscillation taken with Gehrche Oscillograph Tube. (Hans Boas.)

mirror driven at a very high speed. A convenient arrangement is that of Hans Boas (see Fig. 35), in which a small continuous current motor driven at a very high speed has on its shaft a polished metal mirror, concave or plane, according to whether it is for eye observation or for photographs. The mirror reflects an image of the electrodes of the oscillograph tube on to the eye, or the photographic plate, and then at intervals, when a discharge takes place at the moment when the mirror is in the right position, the eye will perceive an image as in the photograph in Fig. 34, which consist of separated-out images of the discharges taking place with each oscillation. When photographed on a plate, the frequency of these oscillations can be determined if the number of revolutions of the mirror per second is known, and also the distance of the mirror from the plate.

Probably the most exact confirmation of the truth of the Kelvin formula (20) for the natural time period of a low resistance oscillatory

circuit has been furnished by the measurements made by Glazebrook and Lodge on the oscillatory discharge of an air condenser employed as a means of determining the value of "v," or the ratio of the electromagnetic and electrostatic units.

In the formula for the time period $T = 2\pi\sqrt{CL}$, let us suppose that capacity C is measured in electrostatic units, and L in electromagnetic units. Then, since an electromagnetic unit of capacity is v^2, or 9×10^{20} times larger than an electrostatic unit, we have to introduce a factor and write the formula in the form—

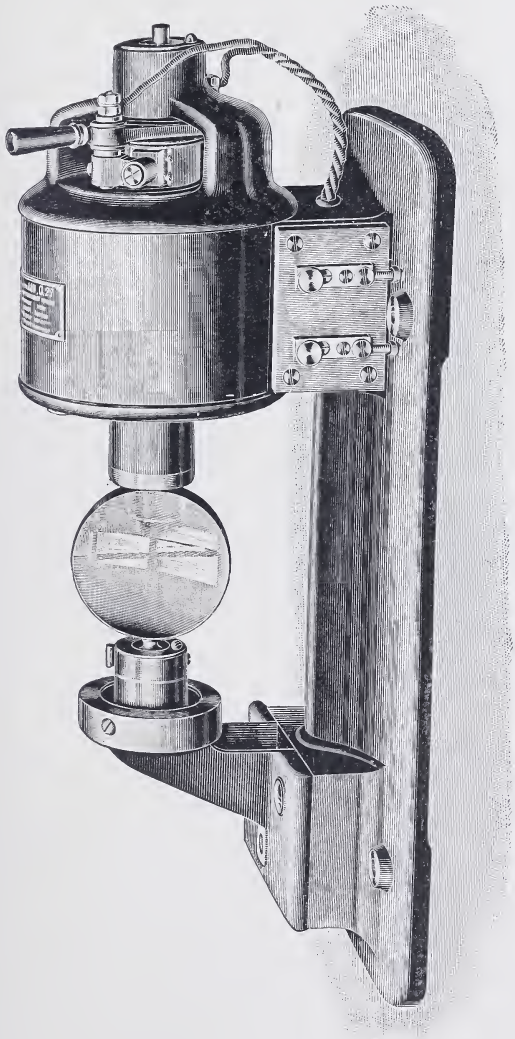


Fig. 35.—Electric Motor driven Rotating Mirror for use with the Gehrche Oscillograph Tube. (Hans Boas.)

$$T = \frac{2\pi}{v}\sqrt{CL}$$

where C is capacity measured in electrostatic units, and L is inductance measured in centimeters or electromagnetic units. Glazebrook and Lodge used this expression to determine the value of v from measurements of T, C, and L (see *Cambridge Philosophical Transactions*, vol. 18, p. 136, 1900), and found that

$$v = 3{\cdot}009 \times 10^{10}.$$

From numerous determinations of "v" by other methods, its numerical value is known to be very near 3×10^{10}. Hence the fact that the numerical values of T determined by this last formula, when we are given the numerical values of C, L, and v, agree with the periodic time found by the measurement of photographs taken of the discharge spark of the circuit on a revolving photographic plate, affords strong proof of the accuracy of the formula.

7. Apparatus for the Production of Damped Trains of Intermittent Electric Oscillations.—The usual method employed

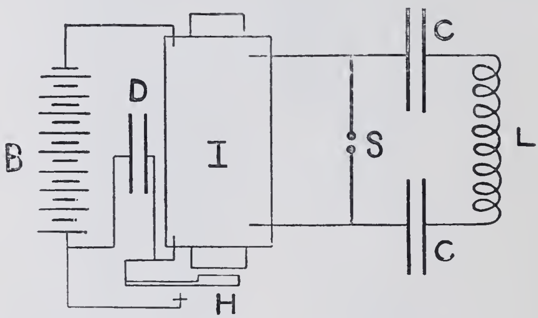


Fig. 36.—Diagrammatic Representation of the Arrangement of Apparatus for the Production of damped Electric Oscillations. B, battery; I, induction coil; S, spark balls; C, C, condensers; L, inductance coil; H, hammer break; D, coil condenser.

for the production of damped electric oscillations is the intermittent discharge of a condenser of some kind, the charge and discharge being repeated at regular and frequent intervals.

The arrangement consists of a condenser suitable for being charged to a high potential, which is then discharged through an inductance of low resistance, thus creating a train of oscillations, and this process is repeated several times in a second.

One of the simplest and most convenient arrangements consists in connecting to the secondary terminals of an induction coil a high tension condenser, such as a Leyden jar or jars, joined in series with an inductive resistance. The secondary terminals of the induction coil are provided with spark balls, or else connected to a separate ball-discharger, and the arrangement is as shown diagrammatically in Fig. 36, and in perspective in Fig. 37. When the induction coil is set in action, at each interruption of the primary current an electromotive force is created in the secondary circuit. This charges the condenser, and if the spark balls are placed at a

suitable distance apart, easily found by trial, the electromotive force breaks down the insulation of the air between the spark balls when it reaches a certain value, and the charged condenser then discharges across the spark gap and creates electric oscillations in the inductance coil. This process is repeated at every interruption of the primary circuit of the coil, and if the adjustments are properly made, it results in the production of a continuous noisy spark between the spark balls, which is in fact a continuous series of oscillatory discharges with short intervals of time between them, corresponding to the groups of electric oscillations produced in the inductive circuit.

In place of an induction coil, any other type of generator of high electromotive force might be employed; such, for instance, as an electrostatic machine, a voltaic battery of a large number of cells, a continuous or alternating current dynamo, or an alternating current transformer. If, however, a voltaic battery, continuous current high

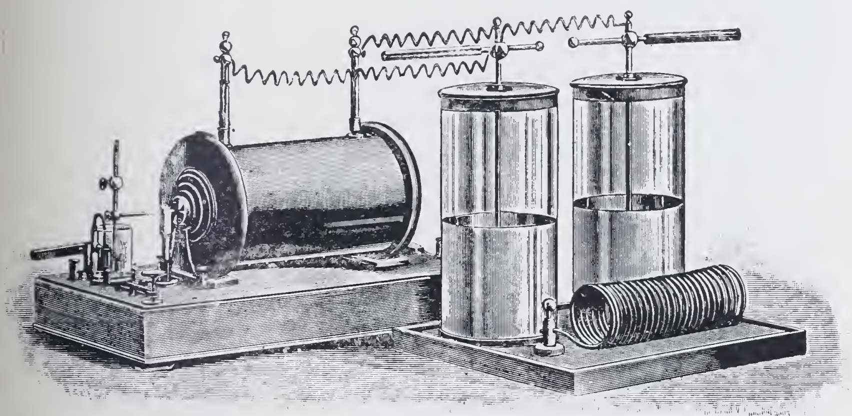


FIG. 37.—Perspective View of the Arrangement of Apparatus for the Production of damped Electric Oscillations, consisting of an Induction Coil, Condensers (Leyden Jars), Spark Gap, and Inductance Spiral.

tension dynamo, or alternating current transformer, is employed, the arrangement will not operate well unless some means are used to continually destroy or prevent the electric arc discharge which tends to be produced and maintained across the spark gap. The spark which occurs at this gap must consist wholly, or nearly entirely, of the discharge coming from the condenser, and not have superimposed on it any true electric arc discharge, either continuous or alternating, proceeding directly from the source of the electromotive force. We shall discuss in a later section the various devices for controlling the operation of the electric generator in this respect. In the majority of cases, the most convenient source of electromotive force is found to be either a large induction coil, the primary circuit of which is traversed by an interrupted continuous current or alternating current, or else the employment of some form of alternating current transformer.

We proceed to consider in further detail the practical arrangements which have to be employed. It is essential that the source of

electromotive force, whatever its nature, shall not only be able to create a large difference of potential between the surfaces of some form of condenser, but shall also be able to supply a certain minimum electric current. Hence, for many purposes, an electrostatic electrical machine would be unsuitable, because although capable of producing a large difference of potential, it acts like an electric generator of very high internal resistance, and therefore the current which can be obtained from it, that is, the rate of supply electricity, is very small. The employment of voltaic cells, or secondary batteries, as a source of electromotive force, presents many advantages, but the very large number of cells required and the expense of maintaining them in order renders this form of electromotor more suitable for special research purposes than for general use.

Professor Trowbridge has employed a battery of 20,000 small secondary cells, giving an electromotive force of 42,000 volts, in special researches on electric oscillations. For this purpose high potential continuous current dynamos have also been used, but although the difficulties involved in the commutation of these high potential continuous currents have been overcome, at least as far as the construction of continuous current dynamos up to 10,000 volts is concerned, yet the complications which are involved in the use of the continuous current do not compensate for the other advantages.

Hence practically we are limited at the present moment to one of two appliances as a source of high electromotive force for charging the necessary capacity, viz. either an induction coil or an alternating current transformer.

In the next place, we have to provide some form of condenser to receive and store the energy. This must be one capable of being charged to a potential of 20,000 volts, or more, as otherwise the oscillations produced are very feeble. The condenser has to be placed in series with an adjustable spark gap and with an inductance which generally consists of the primary circuit of an air core transformer, called an oscillation transformer.

In the next place, there must be means, such as certain choking coils or inductances, for preventing the formation of an electric arc between the spark balls, and, lastly, a key for controlling the operation of the arrangement at pleasure. Accordingly, there are seven elements in the complete oscillation-producing appliance, which are as follows :—

1. The induction coil transformer or source of electromotive force (T).
2. The condenser (C).
3. The discharger or spark balls (D).
4. The arc quenching inductances (Q).
5. The oscillation transformer (PS).
6. The adjustable inductance for varying the period (L).
7. The controller or key in the primary circuit of the coil or transformer (K).

These several elements have each to be considered separately with reference to their best practical forms for various purposes.

Diagrammatically, the complete appliance for producing trains of damped electric oscillations is as shown in Fig. 38, where the letters

have reference to the parts or elements 1 to 7 as enumerated above.

When the key K is closed, and the apparatus in operation, we have trains of intermittent decadent electrical oscillations set up in the circuit CPL, and if the terminals of the secondary circuit S of the oscillation transformer are near together, we have high potential high frequency oscillatory sparks passing between them.

There are certain modifications of the above arrangement which will be considered later, but the above-described apparatus in a typical form is generally called a Tesla apparatus for the production of high frequency electric currents.

8. Induction Coils for creating Electric Oscillations.—It is not necessary to occupy space with any elementary explanation of the construction of the induction coil. A coil very generally employed for the production of electric oscillations is that known as a 10-inch coil, that is, one which is capable of giving a 10-inch spark between pointed conductors in air at the ordinary pressure (see Fig. 39). The

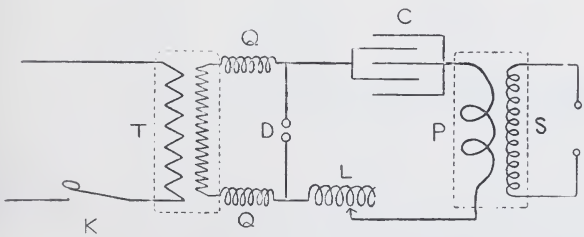


Fig. 38.—Arrangement of Apparatus for producing damped High Frequency Electric Oscillations by means of an Alternating-Current Transformer.

construction of a large induction coil is a matter requiring very great technical skill, and should not be attempted without considerable previous experience in the manufacture of smaller coils.[20] A coil of the above size usually has a primary circuit consisting of a length of 300 or 400 feet of insulated copper wire, No. 12 or No. 14 S.W.G. The secondary circuit would consist of a double silk-covered copper wire, No. 34 or No. 36 S.W.G., a length of 10 to 17 miles of wire being employed, according to the diameter of the wire selected. It is necessary to wind the secondary circuit of such a coil in a large number of flat sections, the sections being prepared separately, and each carefully insulated with paraffin wax and discs of shellaced paper, the coils being so wound in two layers that there are no joints between sections at the inside, but all soldered junctions are at the outside ends. A number of such sections, varying from 100 to 500, are employed in building up the secondary coil, and these are slipped on to a thick ebonite tube, in the interior of which is placed a primary circuit and the iron core.

[20] Detailed instructions for the manufacture of large induction coils are given in a "Treatise on the Construction of Large Induction Coils," by A. T. Hare (Methuen & Co.). Particulars of many large coils are given in a treatise on "The Alternate Current Transformer," by J. A. Fleming, vol. ii. chap. 1 (the Electrician Printing and Publishing Co., Ltd., 1, Salisbury Court, Fleet Street, E.C.).

A special form of winding machine has been invented by Leslie Miller (British Pat. Spec., No. 5811 of 1903) for winding the flat sections of the secondary bobbin, so that no joints at all between sections are necessary, the secondary wire being continuous from end to end. (See Fig. 40.)

By this invention the secondaries of induction coils and transformers can be wound in a manner not hitherto accomplished. The secondary bobbins in induction coils, made to give from 10- to 18-inch sparks, are built up in the Miller process of 700 to 1200 separate single wire sections, with a disc of paper between each section, the wire being continued from one section to the other without any joint. The method of winding will be readily understood from the diagram in Fig. 40. For the sake of clearness, this diagram shows the sections

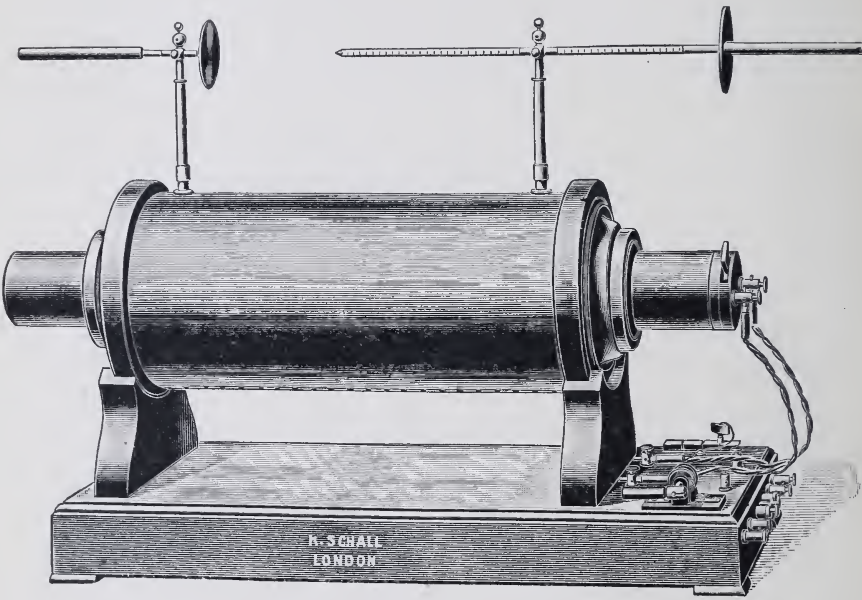


Fig. 39.—10-inch Spark Induction Coil.

widely separated from one another, whereas in reality they are closely compacted together.

The construction of the secondary circuit must be such that no parts of the secondary wire, which are at great differences of potential when the coil is in action, are near together, and one very important point is the construction of the secondary in a sufficient number of flat sections. Another essential detail is the sufficient insulation of the secondary bobbin from the primary coil. With this object in all large induction coils, the primary circuit and its iron core are entirely enclosed in a stout ebonite tube, the walls of which must be at least half an inch in thickness, and it should preferably be overlaid with a layer of paraffin wax an inch in thickness. On the compound tube so formed the sections forming the secondary circuit of

the coil are slipped. When the sections in the secondary circuit have all been joined up and the connections well insulated, the whole of the secondary circuit should be compressed and immersed in molten paraffin wax. This is best done by enclosing the secondary circuit in an iron box of the required size, which, after being closed, is heated and the air exhausted from it. Molten paraffin wax is then allowed to flow in under pressure and set solid. In this manner the entire secondary circuit is penetrated with paraffin wax, and the production of vacuous spaces as the wax cools is prevented. The silk-covered copper wire employed in winding the secondary should also be heated to a temperature above that of boiling water, previous to being immersed in paraffin wax, during the winding of the secondary sections. When completed, the secondary winding is enclosed in a cylinder of ebonite, and thick ebonite cheeks are fitted to the ebonite tube on which the secondary is wound. As the surface of ebonite deteriorates in insulating quality by exposure to light, it is better to

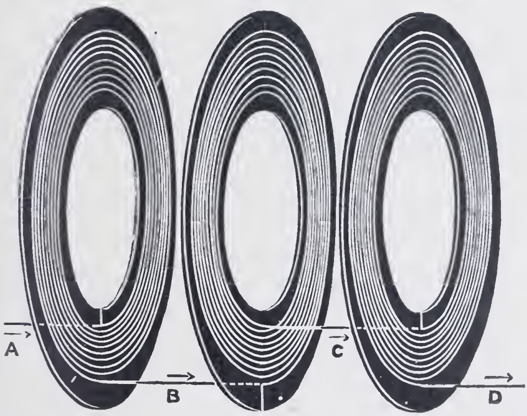


Fig. 40.—Method of building up the Secondary Circuit of an Induction Coil in Sections by Leslie Miller's mode of winding.

enclose the completed induction coil in a wooden box, which is filled in solid with paraffin wax, the ends of the secondary circuit being brought out through thick ebonite tubes, which pass right down into the wax. Instrument makers are too prone to study external appearance in instrument making, and the ordinary type of induction coil, though very suitable for the lecture table, is not at all well adapted for practical use in connection with wireless telegraphy, when the coil has to be used in damp exposed places, such as in a lighthouse or on board ship.

The primary circuit of a 10-inch spark coil generally consists of 360 turns of No. 12 S.W.G. copper wire wound round an iron core consisting of a bundle of soft iron wires, 2 inches in diameter. It has resistance of about 0·46 ohm and an inductance of 0·02 henry. The secondary circuit of such a coil may consist of 17 miles of No. 34 S.W.G. copper wire, making about 50,000 turns. This coil would have a resistance at ordinary temperatures of about

6600 ohms, and when the iron core is in it an inductance of 460 henrys. The mutual induction between the primary and secondary circuits would be about 2·75 henrys, and with a primary current of 10 amperes the coil should give a 10-inch spark. A smaller coil giving a 6-inch spark would usually have a primary circuit with a resistance of 0·426 ohm and an inductance of 0·013 henry. The secondary circuit would be wound with No. 36 S.W.G. wire, which would have a resistance of 9750 ohms and an inductance of 234 henrys, the mutual inductance between the primary and secondary circuit being 1·5 henrys.

An important matter in connection with an induction coil to be used for creating electrical oscillations is to secure a sufficiently small resistance in the secondary circuit. The purpose for which the coil is employed is to charge a condenser of some kind.

If a constant electromotive force V is applied to the terminals of a condenser having a capacity C, the condenser being placed in series with a wire of resistance R, then the full difference of potential V is not created between the terminals of the condenser instantly, but the terminal potential difference rises up gradually and any time t seconds after the contact is made, an expression for its value, v, at that instant may be obtained, as follows :—

Let i be current at the time t in the inductionless resistance R in series with the condenser, then Ri is the fall of potential down this resistance. Also $C\frac{dv}{dt}$ is the current through the condenser and resistance. Hence we must have—

$$CR\frac{dv}{dt} + v = V \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

The solution of this equation is—

$$v = V(1 - \epsilon^{-\frac{t}{CR}}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

In the above equation the letter ϵ stands for the number 2·71828, the base of the Napierian logarithms, and R for the resistance in megohms of the wire in series with the condenser, of which the capacity is C microfarads. This equation shows that the potential difference v of the terminals of the condenser does not instantly attain a value equal to that of the steady impressed electromotive force V, but that it rises up gradually. Thus, for instance, suppose that a condenser of 1 microfarad is being charged through a resistance of 1 megohm, by an impressed constant voltage of 100 volts, the equation shows that at the end of the first second after contact the terminal potential difference of the condenser will be only 63 volts, at the end of the second second 86 volts, and so on. The gradual increase in v with time is shown by the curve in Fig. 41. The equation indicates that only after an infinite time is the terminal potential difference v of the condenser plates equal to the impressed electromotive force V, viz. to 100 volts in this instance. Since, however, ϵ^{-10} is an exceedingly small number, in ten seconds the condenser would be practically charged with a voltage equal to 100 volts. The product CR in the above equation is called the *time-constant*

of the condenser, and we may say that the condenser is practically charged after an interval of time equal to ten times the time-constant, counting from the moment of first contact between the condenser and the source of constant voltage. The time-constant is to be reckoned as the product of the capacity C in microfarads and the resistance of the charging circuit R in megohms. To take another illustration. Supposing we are charging a condenser having a capacity of $\frac{1}{10}$ of a microfarad through a resistance of 10,000 ohms. Since 10,000 ohms is equal to $\frac{1}{100}$ of a megohm, the time-constant would be equal to $\frac{1}{1000}$ second. Hence, in order fully to charge the above capacity through the above resistance, it is necessary that the

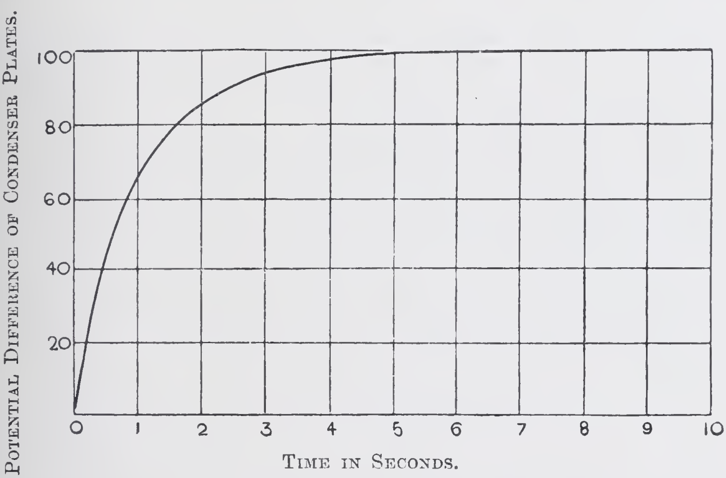


Fig. 41.—Curve showing the Gradual Rise in the Terminal Potential Difference of a Condenser with Time, under a Constant Impressed Electromotive Force of 100 volts, when a Condenser of 1 microfarad capacity is charged through a resistance of 1 megohm.

contact between the source of voltage and the condenser should be maintained for at least $\frac{1}{100}$ part of a second.

We may put the equation (23) in a form more convenient for calculation.

We have $$V - v = V\epsilon^{-\frac{t}{RC}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Hence $$t = RC\left\{\log_\epsilon V - \log_\epsilon (V - v)\right\} \quad . \quad . \quad . \quad (25)$$

or $$t = 2{\cdot}3026\, RC\left\{\log_{10} V - \log_{10}(V - v)\right\}. \quad (26)$$

This last expression can be employed to calculate the value of either of the four quantities v, R, C, or t, when three of them are given.

When an induction coil has its secondary terminals connected to a condenser, we may regard the electromotive force created in the secondary circuit as acting through the resistance of the secondary circuit to charge the condenser.

Hence, in order that the charging of the condenser may be

achieved in the shortest possible time, it is desirable that the secondary circuit of the coil should have as low a resistance as possible, consistent with permissible cost of construction. This involves winding the secondary circuit with a rather thick wire. If, however, we employ a wire much larger in size than No. 34, or, at the most, No. 32, the bulk and the cost of the induction coil begin to rise very rapidly. Hence, as in all other departments of electrical construction, the details of the design are more or less a matter of compromise. Generally speaking, however, it may be said that the larger the capacity which is to be charged, the lower should be the resistance of the secondary circuit of the induction coil.

It is this fact which gives the alternating current transformer, as usually made, an advantage over the induction coil for the purposes considered, because a transformer is merely an induction coil specially constructed for a large power output, and having therefore a secondary circuit of relatively low resistance.

In coils intended for the production of electrical oscillations, and for wireless telegraphy, the preservation of high insulation in the secondary circuit is of great importance. The insulation is then subjected to strains far greater than when the coil is employed for Röntgen ray work or other similar purposes.

A large induction coil is an expensive instrument, but it hardly ever retains for long its pristine powers of spark production. This is due to some degree of failure of internal insulation, or to surface leakage over ebonite surfaces outside, which have deteriorated in insulating power by exposure to light and air.

In those cases where portability is not a principal necessity, an induction coil made with oil insulation may be used and preserves its insulation better than one made in the usual way. If the coil is intended to be used with interrupted continuous primary currents, the iron core must be in the form of a straight bundle of iron, and not in the form of a closed circuit. Hence a so-called open magnetic circuit transformer or induction coil cannot be enclosed in an iron case. It can, however, be placed in a stoneware jar or vessel, and the whole coil can be immersed in insulating oil. For this purpose vaseline oil or heavy resin oil may be employed, provided it has been perfectly freed from water by heat. It is desirable to employ an oil with density greater than that of water, and to seal the jar as perfectly as possible. The secondary winding must be in sections as usual, but need not be impregnated with paraffin wax.

Induction coils intended for use on board ship for wireless telegraph purposes require especially good insulation, and should be so perfectly water-tight that the coil is not injured by even being put under water. If ebonite covering is used to enclose the coil, it should then be overlaid with a thick coating of paraffin wax and resin.

Preferably the coil should be contained in a teak box filled in solid with paraffin wax and resin, in which case it can be screwed up against a bulkhead.

In the case of coils worked with an interrupted continuous primary current, it is necessary to place a condenser (called the primary condenser) across the point of rupture of the primary circuit, where the

break spark occurs to reduce the spark and annul the magnetism of the core more suddenly.[21]

Instrument makers generally determine by trial for each particular coil the proper size of condenser, and fix it in a box which supports the coil.

A better plan is to provide in a separate box a condenser divided into sections, the capacity of each section being marked on it, so that the capacity used may be varied. The condenser generally consists of sheets of well-baked and paraffined bank post paper, alternated with tinfoil sheets an inch narrower than the paper but of the same length.

In the usual construction sheets of tinfoil are placed alternately with double or treble sheets of paraffined paper between them, and the sheets of tinfoil arranged to project out alternately on one side and the other. The odd and even sheets are then respectively clamped together.

The capacity of a condenser of this kind may be very roughly reckoned as equal to 0·01 mfd. per square foot of effective tinfoil surface.

Considerable difference of opinion exists between coil builders as to the capacity of the condenser suitable for use with a 10-inch coil. Some makers would use a primary condenser of 1·25 mfd. capacity; others one as small as 0·5 or even 0·32 mfd. for the above size of coil. Provided the capacity of the condenser is not too small, it may be varied within somewhat wide limits without objection, but if a platinum hammer break is employed, it is better to err in the direction of using too much rather than too little capacity. Even with a 6-inch coil having a hammer break, some makers provide a primary condenser of 1 mfd. capacity.

The question of the right primary capacity to employ with any given coil and break has been investigated by Dr. J. E. Ives; he observes that—

> "The *optimum capacity* of an induction coil is defined to be that capacity which if placed across the break will give the longest spark in the secondary circuit. It has also been found by experiment to be the least capacity that causes the sparking at the break to disappear—if not entirely to disappear, to become very small."[22]

Ives carried out experiments with a hand-worked mercury break in which the primary current was interrupted by raising an amalgamated copper wire out of mercury covered with water. He calls the copper wire the breaking pole, and found that the optimum

[21] For a theory of the action of the condenser, the reader may be referred to the author's "Treatise on the Alternate Current Transformer," vol. ii. p. 51, where it is suggested that the efficacy of the condenser may depend upon the demagnetizing action on the core of the electric oscillations set up in the circuit of the primary coil and condenser at the moment when the condenser is thrown into the circuit.

For another view of the action of the condenser, the reader is referred to a very interesting paper by Lord Rayleigh, in the *Philosophical Magazine* for December, 1901, ser. vi. vol. 2, p. 581, "On the Induction Coil," in which the principal, if not the only, function of the condenser is shown to be that of quenching the spark or arc at the contact points when the primary circuit is opened.

[22] See "Contributions to the Study of the Induction Coil," by J. E. Ives, *Physical Review*, vol. xiv. No. 5, May–June, 1902; also vol. xv. No. 1, July, 1902. Also J. E. Ives, "On the Law of the Condenser in the Induction Coil," *Phil. Mag.*, October, 1903, ser. vi. vol. 6, p. 411.

capacity was much greater when the breaking pole is negative than when it is positive for the same current broken.

His conclusions are that in general the optimum capacity is proportional to a power of the primary current greater than the square but less than the cube. It depends very much upon the resistance of the connections leading to the break and condenser, increasing with these connection resistances. It is also to some extent affected by the inductance of the primary circuit.

The capacity required is, however, in a considerable degree determined by the nature of the break employed. It has been shown that the more sudden the rupture of the primary circuit, the less the capacity necessary, and if that break is very sudden, then the addition of a condenser across the rupture point is not necessary.

Professor J. Trowbridge has described an effective form of quick motor break for large coils, in which the interruption is caused by withdrawing a stout platinum wire from a dilute solution of sulphuric acid, and by this means he increased the length of spark given by a coil originally provided with a hammer break and condenser from 15 to 30 inches by using the liquid break and no condenser.[23]

Lord Rayleigh has also shown that if the interruption of the primary circuit is extremely sudden, as when it is severed by a bullet from a gun, the primary condenser can be removed, and yet the sparks obtained from the secondary circuit are actually longer than those obtained with a condenser and the ordinary hammer break.[24]

In the use of the coil with any ordinary break, except the Wehnelt (see next section), a condenser of suitable capacity, joined across the break points, increases the secondary spark length. For additional information on this subject the reader is referred to the following papers :—

T. Mizuno, "On the Function of the Condenser in an Induction Coil," *Phil. Mag.*, 1898, vol. 45, p. 447.

K. R. Johnson, "On the Theory of the Condenser in an Induction Coil," *Phil. Mag.*, 1900, vol. 49, p. 216.

R. Beattie, "The Spark Length of an Induction Coil," *Phil. Mag.*, 1900, vol. 50, p. 139.

On the whole it cannot be said that the information is yet very precise on the subject of the size of condenser or capacity to be used. It varies with many factors, and hence the necessity for providing the coil with a primary condenser of variable capacity for use in different experiments.

In induction coils by some makers, the primary circuit is wound in sections and the ends of each brought out in such a manner that the various sections can be joined in series or parallel, so as to vary the resistance and inductance of the coil, as well as the effective number of turns.

An ingenious arrangement of this kind is placed on coils by K. Schall, in which the various primary circuits have their ends connected to brass plates, and by sliding into a groove an ebonite piece

[23] See Prof. J. Trowbridge, "On the Induction Coil," *Phil. Mag.*, April, 1902, ser. vi. vol. 3, p. 393.

[24] See Lord Rayleigh, "On the Induction Coil," *Phil. Mag.*, December, 1901, ser. vi. vol. 2, p. 581.

with brass plates upon it these serve to effect the required arrangements and connection. The diagram in Fig. 42 shows the end of the ebonite tube, containing the primary coils, and also the connecting plates which are slipped in to effect various combinations of the different primary circuits, so as to put them (1) all in series, (2) all in parallel, or (3) in series-parallel in various ways.

In making an estimate of the value of a coil for wireless telegraph purposes, or for the production of electric oscillations, the experimentalist should not be guided merely by external appearance or even by the length of spark given between pointed terminals in air.

The resistance of the secondary circuit should be ascertained, and inquiry made into the power of the coil to give a good oscillatory spark of at least 1 cm. in length when the secondary terminals are connected to a condenser having a capacity, say, of $\frac{1}{100}$ mfd.

A very fair way to judge the value of a coil for this particular

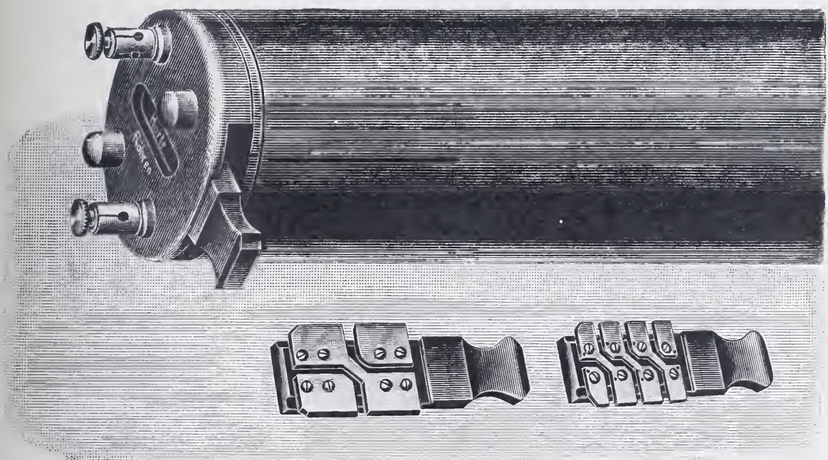


FIG. 42.—End of Primary Coil Tube of an Induction Coil by K. Schall.

purpose is to ascertain what length of secondary spark it will give between brass balls 1 cm. in diameter when these balls are connected to the two poles of a glass plate condenser having a capacity of $\frac{1}{30}$ mfd. The spark should be at least 5 mm. in length.

A coil of the ordinary type, giving a 10-inch spark in air between pointed conductors, will not give much more than a 6- or 7-mm. spark, even if as much, when the secondary terminals are joined to the plates of glass condensers having a capacity of $\frac{1}{18}$ mfd.

When it is desired to obtain the advantages of a very low secondary resistance to charge large condensers, and thus obtain a longer oscillatory spark than can be obtained with one coil, two induction coils may be used with their secondary circuits joined in parallel and their primary coils joined in series. In this case only one hammer break is employed, and the condensers of both coils are joined in parallel across the break. This can always be done when the ends of the primary coil are accessible.

To aid the experimentalist in making these connections, we give below a diagram (see Fig. 43) which shows the usual mode of connecting up the various parts of an ordinary induction coil of the usual pattern with hammer break. This applies to the coils made by English makers such as Apps, Newton, Marconi's Wireless Telegraph Company, Ltd., and others who follow the same pattern. The diagram represents part of the base board of the coil, and the dotted lines show the wire connections which are made in the baseboard box.

The board generally has on it two terminals at one side marked P and N (see Fig. 43). To these the working battery is attached, a fuse wire, F, being interposed; also, as above stated, an ammeter and a Morse key when the coil is used for wireless telegraphy. The end of the iron core of the coil is represented by I, and the hammer break by H. The platinum terminals between which the rupture of the primary circuit takes place are represented by T. On the other side are seen four terminals marked C_1, C_1, C_2, C_2. The two pairs C_1, C_1, and C_2, C_2 are generally connected by small brass pins, *p*, *p*, ending in ivory

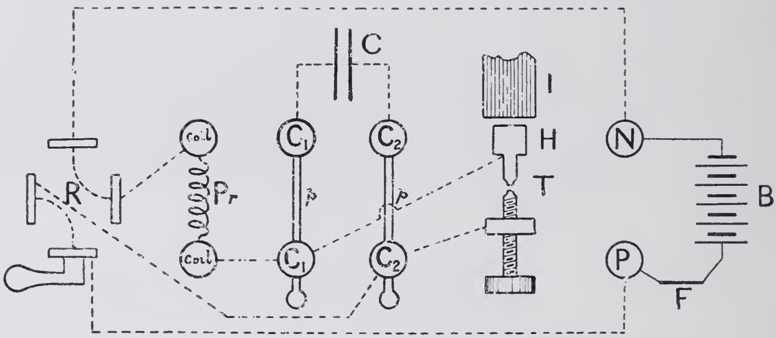


Fig. 43.—Diagram showing the Usual Connections of an Induction Coil.

knobs. To one pair C_1, C_2 are connected the plates of the primary condenser C. If the pins *p*, *p* are withdrawn, then the condenser C is isolated. Beyond are two other terminals marked *coil*. These are the ends of the primary coil of the induction coil. The current reverser is marked R. The connections under the base are denoted by dotted lines. If it is desired to work the coil with the usual hammer break, all that has to be done is to connect a working battery of the right size and number of cells to the terminals P and N, and then adjust the break and throw over the reverser handle to one side or the other.

If, however, it is desired to use some other break, then the pins *p*, *p* must be withdrawn and the required break connected in series with the battery used and with the primary coil. The terminals T must then be kept open by inserting a wooden wedge between them.

Separate wires must then be brought from the condenser terminals to the opposite sides of the particular break used, so that when the circuit is opened the condenser C is thrown across the break point. If coils have to be used in series, then the mode of arranging the

connections can easily be worked out from the diagram of connections in Fig. 43.

The coils used for Röntgen ray work, and also for wireless telegraphy, are now often constructed without breaks and condensers on the same base board, and are intended to be used with some form of separate break (see section 10 of this chapter), and a separate condenser of a capacity suitable for the voltage and primary coil employed.

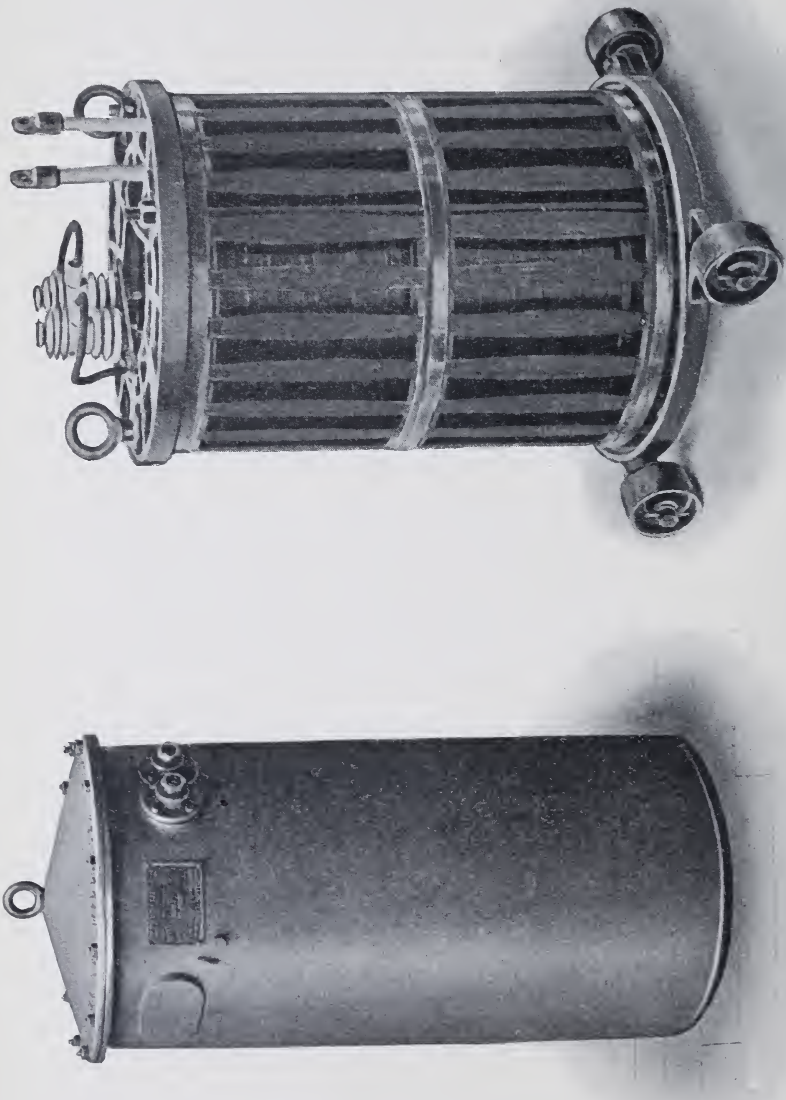
A practical precaution which it is advisable to adopt when working an ordinary pattern induction coil off secondary cells as a source of primary electromotive force is to insert a fuse wire in between the cells and the battery. If the hammer break sticks, as it often does, then the secondary cells send a large current through the contact, and this often welds the platinum contacts together. The use of a fuse wire or other form of cut-out may prevent damage to the break. It is always desirable to insert also an ammeter in the primary circuit, and also a voltmeter across the terminals of the battery to show the current and voltage acting on the primary circuit.

9 Alternators and Transformers for generating Electric Oscillations.—When alternating current is available, an alternating current transformer can be used advantageously for producing electric oscillations in place of an induction coil operated by continuous currents. An ordinary induction coil can also be employed as an alternating current transformer, if its condenser and break is removed and the primary circuit supplied with an alternating current. The frequency of the primary current employed should not be less than 50 periods per second, and it is better, if possible, to work with a much higher frequency, say 500 periods per second.

If continuous current is available which can be drawn from supply mains, from a private electric lighting circuit, public town supply, or from ship lighting circuits on board vessels, then we may employ it to drive a motor generator, producing alternating current from a continuous current. The best plan for so doing is to use an ordinary four-pole continuous-current motor with an armature of the Gramme ring type and the usual commutator. From two points at the opposite ends of a diameter of the armature, connections are brought to two insulated slip rings, fixed on the shaft of the motor. When a continuous current is passed into the motor on the commutator side in the ordinary manner, it revolves, and we can draw from brushes pressing against the slip rings, an alternating current, the effective voltage of which is, however, less than that of the continuous current supplying the motor. Thus, if the motor is driven by direct current at a pressure of 100 volts and makes 1200 revolutions per minute, we can, from the slip rings so connected, draw off an alternating current with an effective voltage of 70 volts and a frequency of 20 periods per second. By the use of a four-pole motor, we can obtain a frequency of 100 when the motor is driven at a speed of 3000 R.P.M.

The alternating current so generated can be led to an alternating current transformer of the closed iron circuit type, and by means of it raised in pressure to 20,000 or 30,000 volts. A suitable form of transformer for this purpose is shown in Fig. 44, made by the British

Electric Transformer Company. Thus if the transformer has a transformation ratio of 400 to 1, we can by means of it produce an



(a) (b)

FIG. 44.—High-tension Oil Insulated Alternating Current Transformer (Berry) for creating Electric Oscillations. (*a*) In Iron Case. (*b*) Transformer removed from Case.

alternating current having an electromotive force 28,000 volts from a continuous current supply at 100 volts. For laboratory purposes,

a 3-kilowatt (kw.) continuous current motor, arranged as described, associated with a 2-kw. step-up transformer, constitutes a very convenient arrangement. In places where a continuous current cannot be obtained to drive the motor, it may be driven as a dynamo or alternator by means of a pulley and belt, by a small oil engine, thus making an arrangement which is independent of outside aid.

It is essential that the high voltage transformer should be an oil insulated transformer, if pressures are employed higher than 20,000 volts, and particularly if the transformer is used in a place which is at all damp.

When pressures higher than 30,000 volts have to be employed, it is better to join a number of separate transformers in series. Thus, for instance, to obtain alternating current at a pressure of 120,000 volts, four transformers of 30,000 volts or six of 20,000 volts can be arranged with their secondary coils in series. In this case, all the transformers must be exceedingly well insulated by being placed on stands supported on strong porcelain oil insulators. In experimenting with alternating currents of very high pressures, supplied by transformers, and alternators, and used to charge large condensers, the greatest precaution must be taken to avoid accidents or touching a high-tension wire, as the result would in all probability be fatal. The experimentalist should himself have control over the current exciting the transformers or exciting the alternator supplying them, and should disregard no precaution necessary to ensure safety. Means should also be taken to ascertain the frequency of the current. This can, of course, be done at once by counting the revolutions of the alternator or motor, but if the supply of alternating current is obtained from a distance, then, in addition to the voltmeters and ammeters, necessary to show the current going into the transformers and the pressure at which it is supplied, a frequency meter ought to be provided.

One well-known form of frequency indicator is that due to Mr. Campbell, which was developed from a principle first suggested in 1889 by Professors Ayrton and Perry. This instrument depends upon the fact that if a light steel elastic strip is fixed over an alternating current electro-magnet, the strip will be set into strong vibration if the frequency of the alternating current agrees with the time period of vibration of the strip. In the Campbell Frequency Teller a steel strip is pushed forward through a clamp by means of a rack and pinion, the pinion carrying an indicating needle which moves over a scale. An alternating current electro-magnet is placed under the strip, and the time period of vibration of the strip can be varied within certain limits by altering the length of the strip which protrudes beyond the clamp. As long as the time period of the spring is out of agreement with that of the magnet current the spring hardly vibrates at all, but if the pinion is turned until agreement is produced, the strip vibrates vigorously, and, striking against a contact point, makes a loud noise.

Many other forms of frequency teller have been developed for practical use in connection with transformer working, but they nearly all depend upon the principle above explained.

Another form of such resonance frequency teller, by Hartmann and

Braun, of Frankfort-am-Main, is illustrated in Fig. 45. In this instrument a number of musical reeds such as are used in organ-pipes or harmoniums are fixed in a row. Each reed is tuned to a particular frequency, and the whole number comprise a range of frequency extending, say, from 80~ to 110~. These reeds are fixed in a frame, and opposite to them slides an electro-magnet, the coils of which are

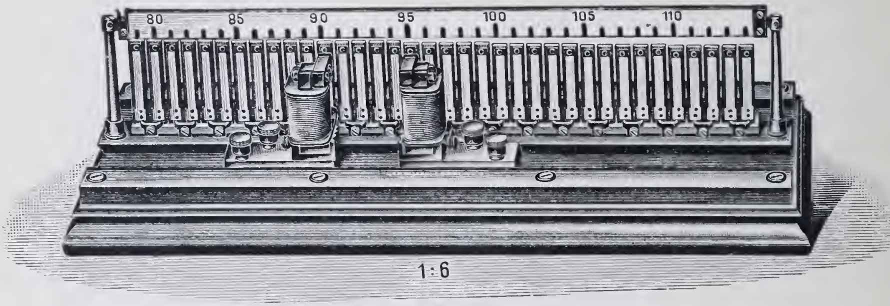


Fig. 45.—Hartmann and Braun Resonance Frequency Meter.

traversed by the current the frequency of which is to be measured. The reeds are made of steel spring, and hence the periodic magnetic field of the magnet sets them in motion. Hence if the alternating current magnet is moved along the row of reeds, when it comes opposite to a reed the natural period of which agrees with the frequency of the current in the magnet, this reed will be set in vigorous vibration and emit a sound, but other reeds will be silent. Therefore from the marking above each reed the frequency becomes at once known. On the other hand, each vibrating reed may have its own magnet, the coils being joined in series and the reeds tuned for different frequencies over a certain range. Then when a current of a certain frequency within this range is passed the corresponding reed is set in vibration, and its movement indicates the frequency. The external appearance is shown in Fig. 46 (see Fig. 45).

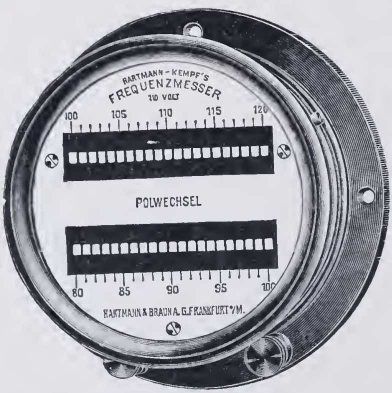


Fig. 46.—Hartmann-Kempf Resonance Frequency Indicator.

A very compact form of apparatus for producing high-pressure high frequency oscillations, employing a motor and transformer as above described, was some years ago described by Professor Elihu Thomson. The following is a description of this apparatus:[25] A small

[25] See *The Electrician*, 1889, vol. 43, p. 779; also *The Electrician*, vol. 44. p. 40. See Prof. Elihu Thomson on "Apparatus for obtaining High Frequencies and Pressures."

continuous current electric motor has in addition to its ordinary commutator a pair of slip rings on the shaft and brushes pressing against them. When the motor is run in the usual way by continuous current, it produces an alternating current at the slip-ring brushes. A step-up transformer is connected to these brushes and raises the pressure to 20,000 volts. The shaft of the motor drives also an insulating frame with metal contact pieces on it, the function of which is to connect together alternately, in series or parallel, a set of glass condenser plates, covered with tinfoil (see Fig. 47). These plates are charged once in each revolution with the secondary terminal voltage of the transformer, but the contact only endures for a short time, during which the potential has its maximum value. During the next part of a revolution, the condenser plates are insulated and connected in

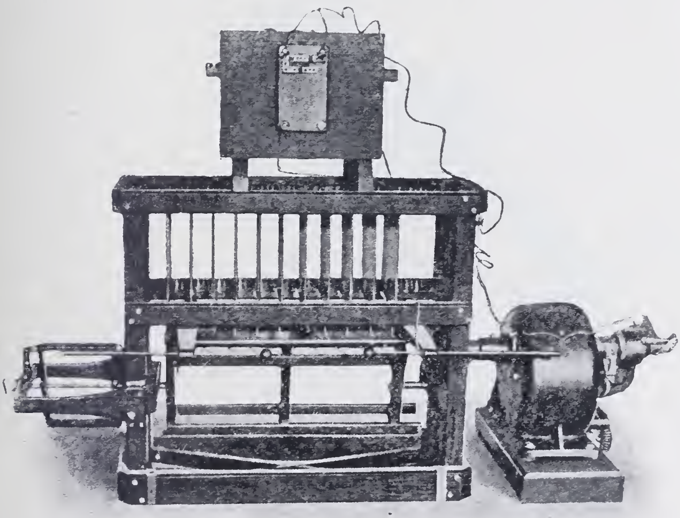


FIG. 47.—Apparatus for producing High Tension and High Frequency Discharges. (Elihu Thomson.)

series and caused to discharge across a spark gap. By employing in this way eleven condenser plates, each one charged at 20,000 volts, a machine was constructed which gave 12-inch sparks in air having all the properties of sparks from an electrostatic machine. These discharges, if the spark gap was small enough, would be oscillatory discharges.

The most convenient arrangement when large power is not required is to use a petrol engine direct coupled to a small rotary converter or continuous current dynamo, having two insulated slip rings on the shaft connected to opposite points on the winding of the continuous current armature. From these slip rings alternating currents can be drawn off and raised in voltage by a transformer.

For some years past the author has possessed in his laboratory such a transformer plant for producing high frequency oscillations. This consists of a four-pole continuous current motor driven at

a speed of 1200 R.P.M.; the motor is provided, as described above, with a Gramme ring armature, and slip rings connected to two opposite points on it, hence the machine produces alternating current at a frequency of 40. This is passed through two transformers arranged in cascade, the first of which steps up the voltage from about 70 to 400, and the second from 400 to about 24,000 volts. The secondary terminals in this last transformer are connected to a large glass plate condenser, the capacity of which can be varied between $\frac{1}{20}$ and $\frac{1}{300}$ mfd. The alternating current motor is 5-kw. size, and the two transformers 2-kw. size. The arrangement is capable of producing very powerful electric oscillations in suitably arranged circuits. A very compact

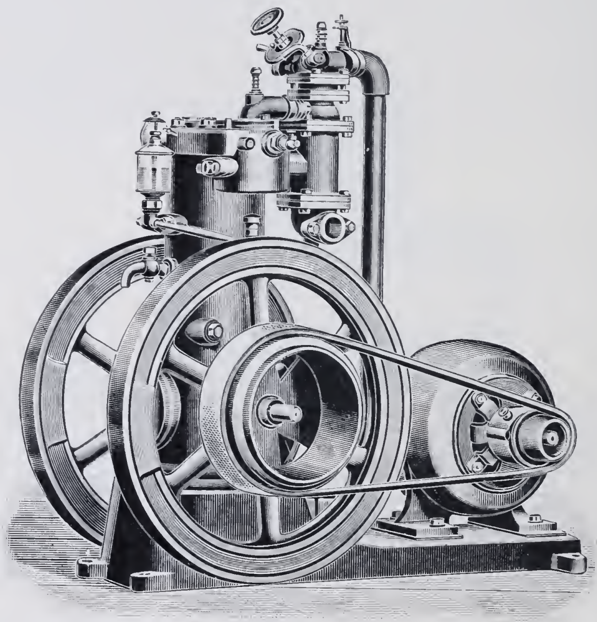


FIG. 48.—Belt-coupled Oil Engine and Alternator for the Production of Electric Oscillations and High Frequency Currents.

plant can also be formed by employing a small oil engine to drive an alternator belt coupled to it and associating with the alternator, as described, a step-up high-tension transformer. This forms a portable arrangement for producing the necessary electric oscillations for wireless telegraphy, when the power required is beyond that capable of being given by an ordinary induction coil (see Fig. 48).

In Fig. 49 is shown in outline the disposition of apparatus necessary for such a transmitter for generating trains of controlled oscillations in an earthed antenna or aerial.

10. Interrupters for Induction Coils.—When a continuous current is employed to actuate an induction coil, it is, of course, necessary to interrupt the primary current periodically, in order to create an electromotive force in the secondary circuit. An important

adjunct, therefore, of the induction coil is the interrupter or break for intermitting the primary current. We may divide interrupters into five classes :—

1. Hammer interrupters.
2. Dipper interrupters.
3. Motor interrupters.
4. Turbine or jet interrupters.
5. Electrolytic interrupters.

We have first the well-known *hammer interrupter*, which Continental writers generally attribute to Neef or Wagner.[26] In this interrupter, the magnetization of the iron core of the coil is caused to attract a soft iron block fixed at the top of a brass spring, and by so doing to interrupt the primary circuit between two platinum contacts. Mr. Apps added an arrangement for pressing back the spring against the back contact, and the form of hammer break that

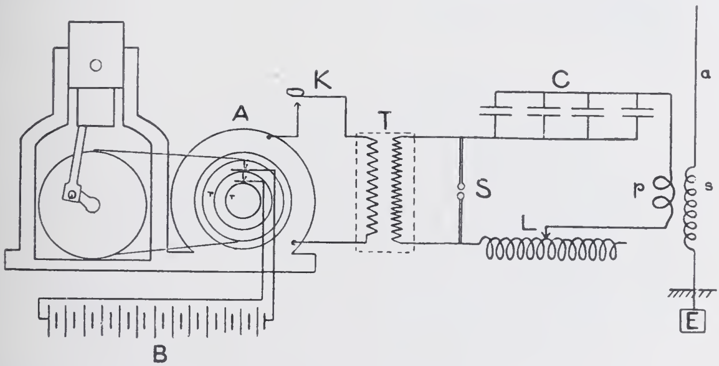


Fig. 49.—Arrangement of Power-plant for the Production of Electric Oscillations and Electric Waves. O, oil engine; A, alternator; T, transformer; S, spark balls; C, condenser; L, inductance; *p*, *s*, oscillation transformer; *a*, antenna or radiator; B, battery for exciting alternator fields; K, key.

is now generally employed is therefore called an Apps break (see Fig. 50).

As the 10-inch coil takes a current of 10 amperes at 16 volts when in operation, it requires very substantial platinum contacts to stand this current continuously without damage. The small platinum contacts that are generally put on these coils by most instrument makers are very soon worn out in practical wireless telegraphy work. If a hammer break is used at all, it is essential to make the contacts of substantial pieces of platinum, at least 6 mms. in diameter, and from time to time, as they get burnt away or roughened, they must be smoothed up with a fine file. It does not require much skill to keep the hammer contacts in good order and prevent them from sticking together and becoming damaged by the break spark.

By regulating the pressure of the spring against the back contact,

[26] Du Moncel states that MacGauley, of Dublin, independently invented the form of hammer break as now used. See J. A. Fleming, "The Alternate Current Transformer," vol. 2, chap. i.

by means of the adjusting screw, the rate at which the break vibrates can be adjusted to make from 10 to 50 or 60 interruptions a second. The hammer break is usually operated by the magnetism of the iron core of the coil, but for some reasons it is better to separate the break from the coil altogether, and to work it by an independent electro-magnet, which, however, may be excited by a current from the same battery supplying the induction coil. For coils up to the 10-inch size the hammer break is sufficiently good when very rapid interruptions are not required. It is not in general practicable to work coils larger than the 10-inch size with a hammer break, as such a platinum contact becomes overheated and sticks if more than 10 amperes is passed through it. In the case of larger coils, we must therefore employ some form of interrupter in which mercury or a conducting liquid forms one of the contact surfaces. On account of its simplicity and ease of management, however, the hammer break is still much used in induction coils employed in wireless telegraphy.

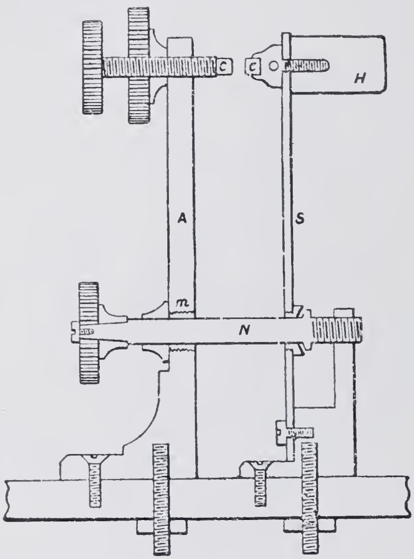


Fig. 50.—Apps' Hammer Break for the Induction Coil.

The second class of interrupter is the self-acting or hand-worked *dipper break*, in which a platinum or steel pin is made to plunge in and out of mercury. This movement may be effected by the attraction of an iron armature, by an electro-magnet, by the varying magnetism of the core of the coil, or it may be effected slowly by hand or rapidly by an electric motor.

The mercury surface must be covered with water, alcohol, paraffin, or creosote oil, to prevent oxidation and to extinguish the break spark. The interruption of the primary current obtained by the mercury dipper break is more sudden than that obtained by the platinum contact in air, at least when the mercury is covered with oil, in consequence of the more rapid extinction of the spark; hence the sparks obtained from coils fitted with mercury dipper interrupters are generally from 20 to 30 per cent. longer than those obtained from the same coil under the same conditions with platinum contact interrupters. The mercury must be cleaned at regular intervals by emptying off the oil or alcohol and rinsing the metal well with clean water, and hence they require rather more attention than platinum interrupters. The mercury interrupter has, however, the advantage that the contact time during which the circuit is kept closed may be made longer than is the case with the hammer break. Also if fresh water is allowed to flow continuously over the mercury surface, it can be kept clean,

and the break will then operate for considerable periods of time without attention.

The hammer or platinum contact interrupter will not work well with an electromotive force of more than 12 or 16 volts, because at higher electromotive forces the break spark prolongs the decadence of the primary current. Hence, if coils are worked on a 100-volt circuit or at higher voltage, some form of mercury break must be employed.

A third kind of interrupter is called a *motor interrupter*, and of these a large number have been invented in recent years. In this interrupter some form of a continuously rotating electric motor is employed to make and break a metal contact with mercury or other liquid. In one simple form the motor shaft carries an eccentric which intermittently dips a platinum point into mercury, or else a platinum horseshoe into two mercury surfaces, making in this manner an interruption of the primary circuit at one or two places. As a small motor can easily be run at 1200 revolutions per minute, or 20 per second, it is possible easily to secure in this manner a uniform rate

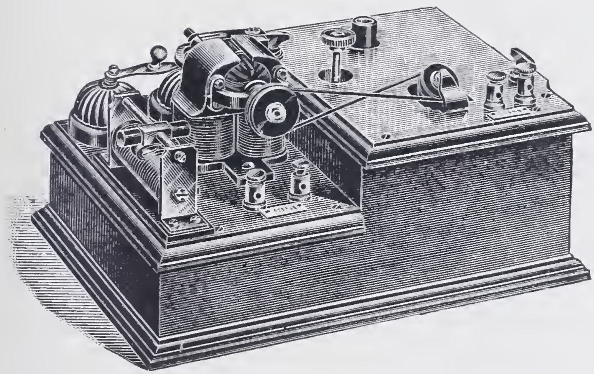


FIG. 51.—Mackenzie Davidson Motor Interrupter.

of interruption of the primary current at the rate of about 20 per second. If, however, much higher speeds are employed, then the time of contact becomes abbreviated, and the power of the coil to charge the capacity is diminished.

One form of motor interrupter invented by Dr. Mackenzie Davidson is illustrated in Figs. 51 and 52. A box contains a vessel one-third full of mercury and the rest of the space filled up with paraffin oil. In this mercury an inclined steel shaft dips. The shaft is rotated by means of an electro-motor belted to it. The speed of the motor can be regulated by a variable resistance. The steel shaft carries at its lower end a slate disc fixed transversely to it. The disc is of such a size that it is only partly immersed in the mercury. The disc is secured to the shaft by a metal pin passing transversely through it, the outer end of the pin being flush with the edge of the disc. As the shaft rotates the outer end of this pin is alternately immersed in the mercury and raised out of it, and therefore puts the steel shaft into electrical connection with the mercury at intervals, depending on the

speed of rotation of the shaft. The inclined shaft is carried in metal bearings, which act as an electrode.

The details of the disc and pin and manner in which contact is made and interrupted by its rotation will be understood from Fig. 52.

When the motor is running slowly the interrupter can be used with a low electromotive force, that is to say, something between 12 and 20 volts; but with a higher speed a larger electromotive force can be employed without danger of passing too much current. With an electromotive force of about 50 volts, the interruptions may be made so rapid that an unbroken arc of flame, resembling an alternating current arc, springs between the secondary terminals of the coil.

Mr. Tesla has also devised numerous forms of rotating mercury break. In one a star-shaped metal disc revolves in a box so that its points dip into mercury covered with oil and make and break contact. In another form a jet of mercury plays against a form of toothed rotating wheel.

For details of these interrupters the reader must consult the fuller

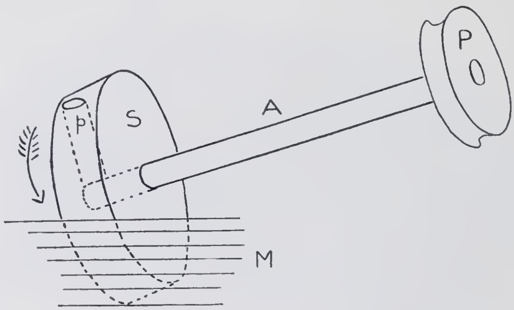


Fig. 52.—Disc and Shaft of Mackenzie Davidson Interrupter. A, shaft; S, slate disc; P, pulley; M, mercury; *p*, contact pin.

descriptions in the *Electrical World*, of New York, 1898, vol. 32, p. 111; or *Science Abstracts*, 1898, vol. 2, pp. 46 and 457.

A fourth class of interrupter is called a *turbine or mercury jet interrupter*. In this appliance a jet of mercury forced out of a small aperture by means of a centrifugal pump is made to squirt against a metal plate, and the jet is interrupted intermittently by means of a toothed wheel made of insulating material, rotated by the motor which drives the pump. Otherwise a revolving jet of mercury is made to impinge intermittently upon a fixed metal plate. The current supplying the coil passes through or along this jet of mercury, and is therefore rendered intermittent when the jet or metal plate revolves. The mercury is covered with paraffin oil or alcohol to preserve the mercury jet from oxidation.

In the case of this interrupter, the duration of the contacts, as well as a number of interruptions per second, is under control, and for this reason, better results are probably obtained with it than with most other forms of break.

A description of a turbine mercury break devised by M. Max Levy was given in the *Elektrotechnische Zeitschrift*, October 12, 1899, vol. 20,

p. 717 (see also *Science Abstracts*, vol. 3, p. 63, Abstract No. 165), as follows:—

A toothed wheel made of insulating material carries from 6 to 24 saw-shaped teeth, and can be made to rotate from 300 to 3000 times per minute by a motor. The teeth of this wheel interrupt a jet of mercury thrown by a centrifugal pump against a metal plate (see Fig. 53). Moreover, by raising or lowering the position of the interrupting wheel by a lever the duration of the contact can be varied, so that it is possible to regulate this period without disturbing the number of interruptions per second. The pump and wheel are contained in a vessel partly full of mercury overlaid with paraffin oil.

The sparks obtained from a coil worked with a turbine interrupter are much thicker and convey a greater electric quantity than the sparks made by hammer breaks. Also by means of the turbine break an induction coil can be worked with a higher voltage than is possible when using a hammer break, and the turbine break has also the advantage of being nearly noiseless in use. By properly adjusting the break, the appearance of the secondary sparks can be varied from the thin snappy sparks given by the hammer break to the thick flame-like arc sparks given by the electrolytic break. The turbine break can be adapted for any voltage from 12 to 250 volts, and the primary circuit cannot be closed before the interrupter is acting.

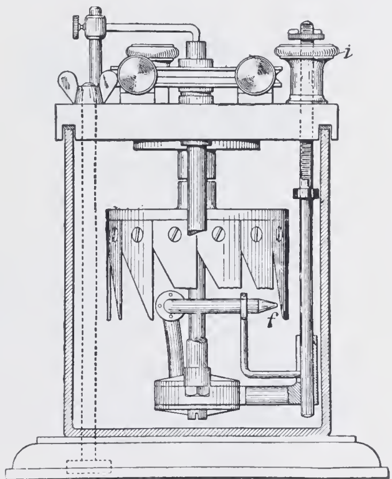


FIG. 53.—Max Levy Mercury Turbine Interrupter.

The chief drawback to its use is that the mercury has to be cleaned at intervals if the interrupter is much used. If alcohol is employed to cover the mercury the metal need only to be rinsed under a water tap and afterwards dried with blotting-paper. When paraffin oil is used the cleaning is more troublesome, but is effected with the help of a few ounces of sulphuric acid. The mercury by use gets gradually resolved into a sort of black mud, consisting of globules of mercury intermingled with oil. If the mud is well shaken up with a little strong sulphuric acid this oily film is removed. The acid is then washed away with fresh water, and clean metallic mercury remains behind.

The motor driving the centrifugal pump can be wound for any voltage, and it is best to have it so arranged that this motor is worked by the same battery as that which supplies the primary circuit of the coil, the two circuits working parallel together. A rheostat can be added to the motor circuit to regulate the speed.

In Fig. 54 is shown a diagram of a good form of mercury jet break by Schall.

A centrifugal pump causes a revolving jet of mercury to impinge against a copper plate. The mercury is contained in a glass vessel, and is covered with paraffin oil, so that the jet of mercury takes place in oil. The duration of the contact can be varied by an adjusting lever which shifts the position of the copper plate.

The motor driving it can be wound for either high or low voltage, and in selecting a break of this kind it is necessary to determine the choice of voltage by the nature of the winding of the primary circuit of the induction coil used with it. Generally speaking, the maker of the coil specifies this to the purchaser.

The great trouble with all these mercury breaks when used with paraffin oil or alcohol as a covering liquid is that the mercury is before long worked up into a sort of black mud and ceases to conduct. M. Béclère, of Paris, made an enormous improvement in substituting coal gas for the insulating liquid. A break of the type shown in

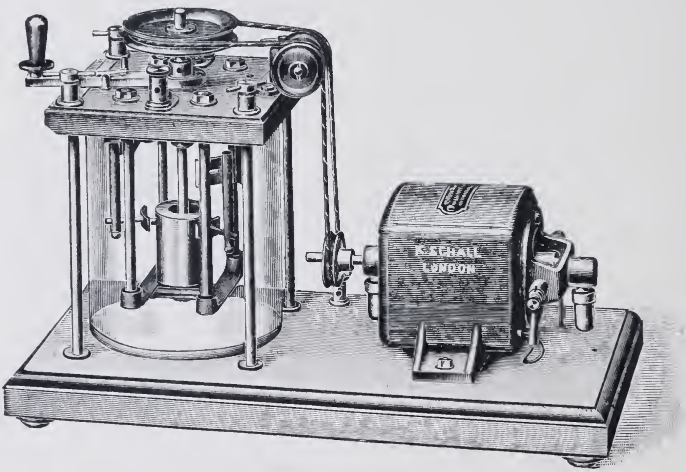


Fig. 54.—Mercury Turbine Interrupter. (Schall.)

Fig. 54 is employed, but instead of filling the space above the mercury with oil it is kept full of coal gas from a small gas-bag which just supplies the loss by leakage. When so modified, the break will work for hours and even months without the slightest attention, and a mercury-coal gas interrupter of this type is now essential in all careful experimental work with the induction coil used as a source of oscillations. A good form of coal gas-mercury break, made by Messrs. W. Watson & Sons, driven by a separate motor, is shown in Fig. 55.

Lastly, we have the *electrolytic interrupters*, which were first introduced by Dr. Wehnelt, of Charlottenburg, in the year 1899, and modified by subsequent inventors. In its original form it consists of a glass vessel filled with dilute sulphuric acid, consisting of one part of strong acid to five or else ten parts of water. This vessel contains two electrodes of very different sizes; one is a large lead plate, formed of a piece of sheet lead laid round the interior of the vessel, and the

other is a short piece of platinum wire projecting from the end of a glass or porcelain tube (see Fig. 56). The smaller of these electrodes is made the positive, and the large one the negative. If this electrolytic cell is connected in series with the primary circuit of the induction coil (the condenser being cut out), and supplied with an electromotive force from 40 to 80 volts, an electrolytic action takes place which interrupts the current periodically. An enormous number of interruptions can, by suitable adjustment, be produced per second, and the appearance of the discharge from the secondary terminals of the coil, while using the Wehnelt break, more resembles an alternate current arc than the usual disruptive spark.[27]

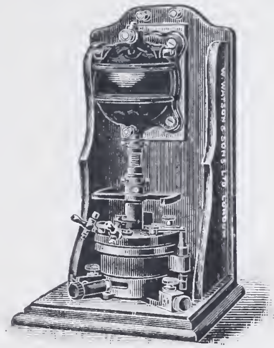


FIG. 55.—Coal Gas-Mercury Turbine Motor driven Break for Induction Coil Working. (Watson & Sons.)

At the time when the Wehnelt break was first introduced, great interest was excited in it, and the technical journals in 1899 were full of discussions as to the theory of its operation.[28]

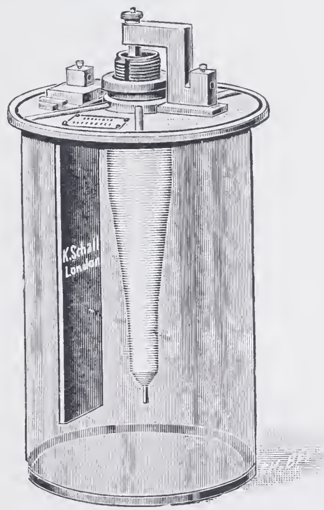


FIG. 56.—Wehnelt Electrolytic Break.

The general facts concerning the Wehnelt break are that the electrolyte must be dilute sulphuric acid in the proportion of one of acid to five or ten of water. The large lead plate must be the cathode, or negative pole, and the anode, or positive pole, must be a platinum wire about a millimetre in diameter, and projecting 1 or 2 mms. from the pointed end of a porcelain, glass, or other acid-proof insulating tube. The aperture through which the platinum wire works must be so tight that acid cannot enter, yet it is desirable that the platinum wire should be capable of being projected more or less from the aperture by means of an adjusting screw. The glass vessel which contains these two electrodes should be of considerable size, holding, say, a quart of fluid, and it is better to include this vessel in a larger outer one in which water

[27] See Dr. Wehnelt's article in the *Elektrotechnische Zeitschrift*, January 20, 1899.

[28] See *The Electrician*, 1899, vol. 42, pp. 721, 728, 731, 732, and 842; communication from Mr. Campbell Swinton, Prof. S. P. Thompson, Dr. Marchant, the author, and others. Also p. 864 of same volume, for a leader on the subject. Also p. 870, letters by M. Blondel and Prof. E. Thomson. See also *The Electrician*, 1899, vol. 43, p. 5, extract from a paper by P. Barry, *Comptes Rendus*, April 10, 1899. See also *The Electrical Review*, February 17, 1899, vol. 44, p. 235.

can be placed to cool the electrolyte, as the latter gets very warm when the break is used continuously. If such an electrolytic cell has a continuous electromotive force applied to it tending to force a current through the electrolyte from the platinum wire to the lead plate, we can distinguish three stages in its operation, which are determined by the electromotive force and the inductance in the circuit. First, if the electromotive force is below 16 or 20 volts, then ordinary and silent electrolysis of the liquid proceeds, bubbles of oxygen being liberated from the platinum wire and hydrogen set free against the lead plate. If the electromotive force is raised above 25 volts, then when there is no inductance in the circuit the continuous flow of current proceeds, but if the circuit of the electrolyte possesses a certain minimum inductance, the character of the current flow changes, and it becomes intermittent, and the cell acts as an interrupter, the current being interrupted from 100 to 2000 times per second, according to the electromotive force and the inductance of the circuit. Under these conditions the cell produces a rattling noise, and a luminous glow appears round the top of the platinum wire. Thus, in a particular case, with an inductance of 0·004 millihenry in the circuit of a Wehnelt break, no interruption of the circuit took place, but with 1 millihenry of inductance in the circuit and with an electromotive force of 48 volts, the current became intermittent at the rate of 930 per second, and by increasing the voltage to 120 volts the intermittency rose to 1850 a second.

The Wehnelt break acts best as an interrupter with an electromotive force from 40 to 80 volts. At higher voltages a third stage sets in; the luminous glow round the platinum wire disappears, and it becomes surrounded with a layer of vapour, as observed by MM. Violle and Chassagny; the interruptions of current cease, and the platinum wire becomes red hot. If there is no inductance in the circuit the interrupter stage never sets in at all, but the first stage passes directly into the third stage. In the first stage bubbles of oxygen rise steadily from the platinum wire, and in the interrupted stage they rise at longer intervals, but regularly. The cell will not, however, act as a break unless some inductance exists in the circuit.

In applying the Wehnelt break to the usual form of induction coil, the condenser and ordinary hammer break are cut out of circuit, and the Wehnelt break is placed in series with the primary coil. In some cases the inductance of the primary coil alone is sufficient to start the break in operation, but with voltages above 50 or 60 it is generally necessary to supplement the inductance of the primary coil by an additional external inductance coil. The best form of Wehnelt break for operating induction coils is the one with multiple anodes (see Fig. 57, also see remarks by Dr. Marchant, in *The Electrician*, 1899, vol. 42, p. 841), and when it has to be used for long periods the cathode may advantageously be formed of a spiral of lead pipe through which cold water is made to circulate.

Another form of electrolytic break was introduced by M. Simon and by Mr. Caldwell. In this a vessel containing dilute sulphuric acid is divided into two parts (see Fig. 58). In the partition is a small hole, and in the two compartments are electrodes of sheet lead.

The small hole causes an intermittency in the current which converts the arrangement into a break. Mr. Campbell Swinton modified the above arrangement by making the partition consist of a sort of porcelain test tube with a hole in the bottom. This hole can be more or less plugged up by a glass rod drawn out to a point. The porcelain vessel contains dilute acid, and stands in a larger vessel of acid, and lead electrodes are placed in both compartments. The current and intermittency can be regulated by more or less closing the aperture between the two regions.

When the Wehnelt break is applied to an ordinary 10-inch induction coil, and the inductance of the primary circuit and the electromotive force varied until the break interrupts the current regularly, with a frequency of some hundreds a second, the character of the

FIG. 57.—Wehnelt Electrolytic Interrupter with Multiple Anodes.

secondary discharge is entirely different from its appearance with the ordinary hammer break. The thin blue lightning-like sparks are then replaced by a thicker mobile flaming discharge, which resembles an alternating current arc, and when carefully examined or photographed is found to consist of a number of separate discharges superimposed upon one another in slightly different positions.

Several hypotheses have been suggested to explain the action of the break, but it is not necessary to consider these in detail. Professor S. P. Thompson and Dr. Marchant have advocated a theory of resonance.[29] One difficulty in explaining the action of the break is created by the fact that it will not work if the platinum wire is made a cathode.

Although the Wehnelt break has some advantages in connection

[29] See *The Electrician*, 1899, vol. 42, pp. 731 and 841.

with the use of the induction coil for Röntgen ray work, its utility as far as regards the production of electric oscillations and its use in electric wave telegraphy is not by any means so marked. It has already been explained that in order to charge a condenser of a given capacity at a constant voltage the electromotive force must be applied for a certain minimum time, which is determined by the value of the capacity of the condenser used and the resistance of the secondary circuit of the induction coil.

If the coil is a 10-inch coil, and has a secondary resistance of, say, 6000 ohms, and if the capacity to be charged has a value, say,

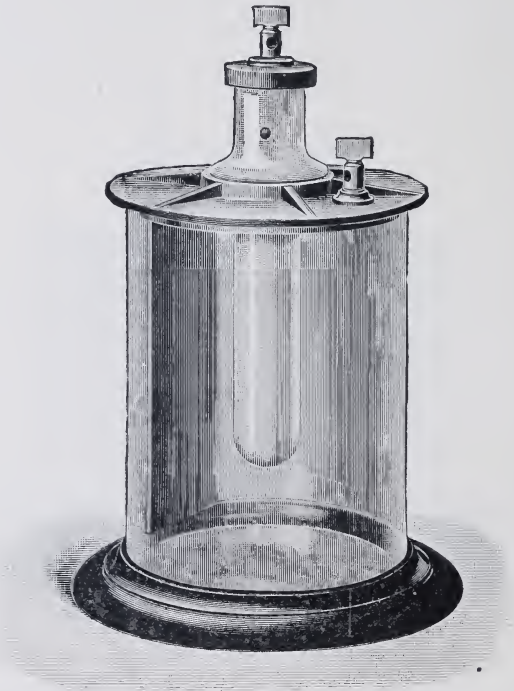


Fig. 58.—Simon or Caldwell Interrupter.

of $\frac{1}{30}$ mfd., then the time-constant of the circuit is $\frac{1}{5000}$ second. Therefore the electromotive force charging the condenser must be maintained for at least $\frac{1}{500}$ second, so that the condenser may become charged to the voltage which the coil is then producing.

In the induction coil the electromotive force generated in the secondary coil at the "break" of the primary current is higher than that at the "make," and the magnitude and duration of this electromotive force, other things being equal, depends upon the rate at which the magnetism of the iron core dies away. Its duration is shorter in proportion as the whole time occupied in the disappearance of the magnetism is less. The Wehnelt break does not increase the actual value or duration of the electromotive force in the secondary

circuit, but it greatly increases the number of times per second this electromotive fôrce is created. Accordingly, it increases the secondary discharge current, but not the secondary electromotive force. Hence, when employing an induction coil to create electric oscillations in an aerial wire, and therefore to send out trains of electric waves, the nature of the receiver or wave detector used determines whether the use of the Wehnelt break is an advantage or not. When using those types of wave detector which are influenced chiefly by the maximum value of the wave train, and not by the root-mean-square value, the increase in the number of wave trains per second produces no additional advantage. Accordingly, the claims at one time made for the Wehnelt break in connection with wireless telegraphy are not borne out by practical experience.

It cannot be denied that the platinum-contact break and all the forms of mercury break with the exception of the Béclère coal gas mercury break, as well as the Wehnelt break, are somewhat troublesome to keep in order. Platinum contacts get rough and stick, and the ordinary vibrating break, though simple in construction, is irregular in action. Hence efforts have been made to abolish the break altogether and yet retain the advantages derived from the use of continuous currents which can be supplied by batteries. One of the best of these is the Grisson electrolytic condenser arrangement.[30] The essential elements are—

An electrolytic condenser of large capacity occupying no very great space. This is constructed of plates of aluminium placed in a special electrolyte, like plates in a secondary cell. The alternate plates are connected together and form the two opposed surfaces of the condenser. If a current is passed in one direction through the cell from one set of plates to the other, a current flows for a short time, but is soon stopped if the E.M.F. does not much exceed 100 volts. This is due to the formation on the anode plates of a film of impervious or non-conducting aluminic hydroxide. If, however, the direction of the current is reversed, the cell again becomes conductive for a short time, and the impervious film is transferred to the other set of plates. Hence the cell acts like a condenser of large capacity, and one equivalent to 100 mfds. occupies a space of only 12 inches by 12 inches by 14 inches.

If a sufficiently large cell of this kind is connected in series with the primary circuit of an induction coil, and a steady E.M.F. of 100 volts or so applied to the terminals, a current flows through the primary for a short time. This current rises very quickly to a maximum value and then dies more slowly away. Hence it creates in the secondary circuit two electromotive forces of very unequal value and in opposite directions. Suppose, then, that by a special commutator the position of the plates of the electrolytic condenser is reversed, another brief current would flow through the primary coil in the same direction and another pair of secondary electromotive impulses be created. This reversal of the position of the plates of the condenser is effected by the use of a revolving motor-driven commutator. At the moment when the condenser is fully charged

[30] This apparatus is supplied in England by Messrs. Isenthal and Co., of 85, Mortimer Street, London, W.

and the current has ceased in the primary coil, the condenser connection with the circuit can be broken *without spark*, and remade with the plates in a reversed direction. Hence the arrangement sends through the primary circuit of the induction coil a rapid series of "puffs" of electric current, and these create secondary electromotive forces which predominate in one direction. This gives us exactly the result we have in the coil as worked with the ordinary break, and does it without spark. A diagram of the connections is shown in Fig. 59, and the general appearance of the condenser and commutator in Fig. 60.

In those researches, in which very regular groups of oscillations must be produced, this apparatus offers a great advantage.

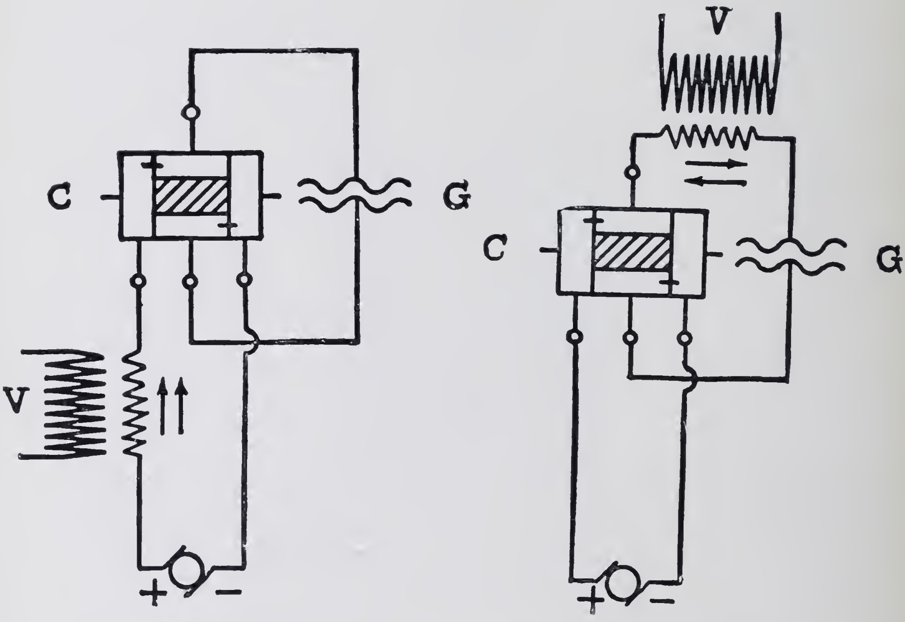


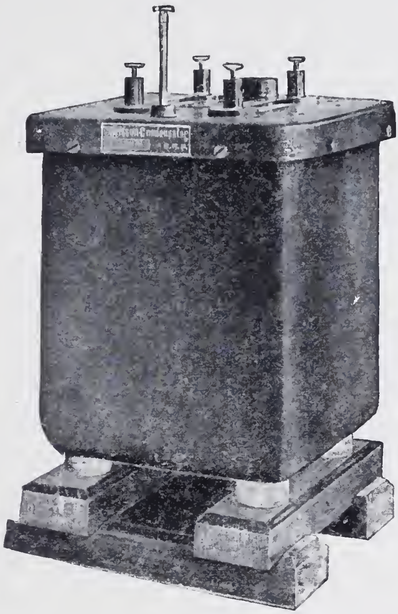
Fig. 59.—Arrangement of Grisson Electrolytic Condenser and Induction Coil. G, electrolytic condenser; C, commutator; V, induction coil.

In another arrangement, also devised by Grisson, an induction coil with a special form of primary winding is employed. The primary coil has three terminals, one at each end and one in the centre of the winding. The centre terminal is connected to one pole of the battery, and the other two terminals are alternately connected to the other pole by means of a revolving commutator. The following operations then take place:—

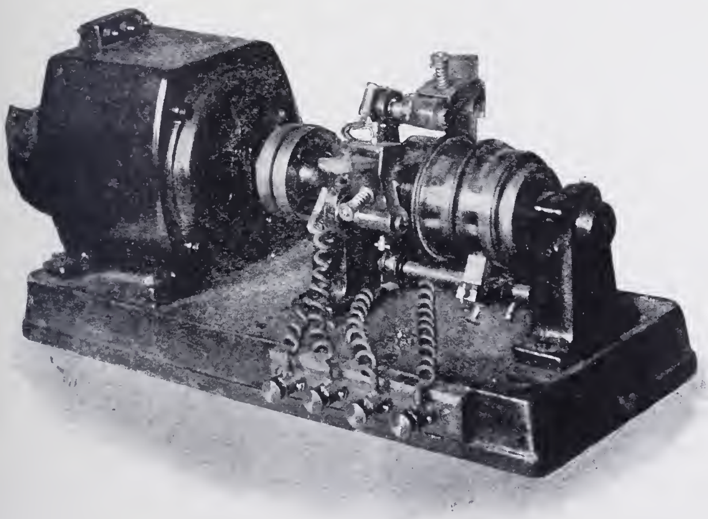
(i.) The primary current flows through one-half of the primary coil and magnetizes the iron core.

(ii.) The current flows in opposite directions through the two halves of the primary winding, and the core has no resultant magnetization.

(iii.) The current flows through the other half of the primary



Grisson Electrolytic Condenser.



Grisson Commutator for use with Electrolytic Condenser.
FIG. 60.

winding, and the direction of the magnetization of the core is reversed.

(iv.) The current again splits and flows equally through both sections of the primary coil, and the core is not magnetized.

These operations are rapidly repeated in the same order. The result is, a series of secondary currents are induced, which are alternately in one direction and the other.

Condensers are placed across the break gaps to quench the spark and exalt the secondary electromotive forces as usual.

These changes of current direction are effected by means of a rotating commutator, consisting of metal segments let into the periphery of a disc of insulating material. Brushes press against this disc, and it is driven round by an electric motor actuated by the source of current supply.

11. Condensers for the Production of Electric Oscillations.—The next element to be considered is the condenser in which the electric charge is placed, the release of which produces the high frequency oscillations.

In this connection we need only consider the construction of condensers suitable for very high pressures. The properties of dielectrics will more particularly be discussed in the next chapter, and we shall here merely discuss the structure of high-pressure condensers.

A condenser essentially consists of a pair of conducting surfaces separated by a dielectric, and the familiar Leyden jar presents itself as an illustration. There are not many solid dielectrics which are capable of being used for charging voltages reckoned in thousands of volts, and the number available for condenser construction is still more limited when questions of cost and internal energy loss in the dielectric are considered.

Glass of certain compositions, ebonite, mica, and micanite, or mica sheets built up with shellac, almost exhaust the list of solid dielectrics suitable for very high pressures. On the other hand, compressed gases and also certain insulating liquids can be usefully employed as dielectrics in the construction of high-pressure condensers. Deferring for the present a further consideration of dielectric properties, it may be said that glass, micanite, and ebonite constitute almost the only available commercial solid dielectrics for condenser construction.

Of these, English flint glass is by far the best material to use, comparing either equal bulks or equal energy storing power, but it is brittle and liable to flaws. Its dielectric constant is high (from 5 to 10), but its dielectric strength is inferior to that of good ebonite or micanite. Ebonite has great advantages for certain quantitative work, as its dielectric constant is constant for a wide range of frequency. Micanite has greater dielectric strength than either glass or ebonite, but its dielectric constant varies considerably with frequency.

A condenser is constructed by applying sheets of flexible metal to the two surfaces of a sheet of dielectric. Usually tinfoil is put upon sheets of glass or ebonite or micanite, or the glass or ebonite may be silvered by an electrochemical process or metallic paint put upon it. By far the most useful process is to stick tinfoil sheets upon glass with some adhesive such as shellac, varnish, siccotine, or isinglass. In the construction of high-tension condensers, no adhesive containing

water, such as gum or paste, should be employed, as the water cannot evaporate. A thin shellac varnish, made up with absolute alcohol or anhydrous methylated spirit or wood naphtha, answers well for glass. The tinfoil sheets must be made to adhere perfectly to the surface of the dielectric, and care taken to exclude air-bubbles. It is much more difficult to secure good adherence between tinfoil and ebonite, but the shellac solution answers well with micanite as the dielectric.

If glass is used it should be a good quality of flint glass, and should be absolutely free from bubbles. Any flaw of this kind is a weak place which sooner or later gives way.

In making an ordinary Leyden jar a considerable margin (at least 25 per cent. of the height) should be left uncovered with tinfoil, and this bare dielectric should be well varnished with anhydrous shellac varnish. The method of securing contact with the tinfoil surfaces is important. The outside coating of the jar should be embraced by a brass strap with a terminal and tightening screw (see Fig. 61), and the brass stem should end in a screw terminal, and should not have the ordinary chain, but be provided with spring extensions, which press tightly against the inner tinfoil surface. The object is to prevent any spark at these contact places, which would quickly pierce the glass. The jars so constructed can easily be joined in parallel or series by the aid of straps of thin sheet copper or stout copper wires.

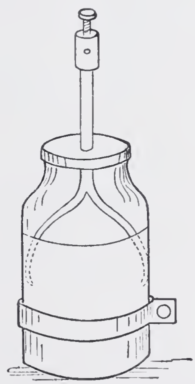


FIG. 61.—Leyden Jar with Spring Clips.

The Leyden jar should always have its capacity measured and marked on it, expressed in fractions of a microfarad. Instrument makers still maintain the absurd custom of denominating Leyden jars as "pint size," "quart size," or "gallon size." The so-called pint size has a capacity of about $\frac{1}{700}$ microfarad, and the so-called gallon size about $\frac{1}{300}$ microfarad.

Glass Leyden jars, as usually made, will stand charging with 20,000 volts. Hence the energy-storing capacity of the "pint size" (being equal of $\frac{1}{2}CV^2$) is about 0·28 of a joule at this pressure, or nearly $\frac{3}{16}$ foot-pound. This is a very small storage compared with the over-all bulk of the jar.

A more satisfactory form of condenser for many purposes may be constructed by covering flat sheets of good flint glass with tinfoil on both sides. The tinfoil sheets should be cut 1 inch smaller each way than the glass plate. The glass should be carefully selected and free from bubbles or flaws, and about $\frac{1}{10}$ or $\frac{1}{8}$ inch (= 3 mm.) in thickness.

The sharp edges should be taken off with an emery wheel. The tinfoil is then stuck on with shellac varnish and the margin of the plate varnished. Each tinfoil sheet must have a wide tinfoil lug attached to it, and the lugs on opposite sides of the same plate must be at opposite corners, but at adjacent corners of neighbouring plates. Plates should be prepared like right- and left-hand gloves, so that when piled one on the other the lugs on the adjacent condenser plates fall upon each other (see Fig. 62). In the diagram, for the

sake of clearness, the plates are shown as widely separated. In actuality they are placed close together. The coated plates should, however, be prevented from coming into absolute contact by discs of card stuck on to the tinfoil by shellac varnish. A pile of any number of such sheets may be made, and when bound together with silk tape may be placed in a stoneware or ebonite box which is filled up with vaseline or double-boiled linseed oil. The oil prevents electric discharge over the edges of the plates. The positive lugs are then all connected to one terminal, and the negative lugs to another terminal placed on the lid of the box.

Glass-plate condensers of the above form can be made without oil insulation if the glass-plate margin beyond the tinfoil is large enough, but the use of oil is essential for very high-tension work.

In some cases glass tubes are employed coated partly outside and partly inside with tinfoil. Test tubes silvered inside and outside for half their height make very convenient small condensers.

Thin glass has a higher dielectric strength than thick glass, and hence nests of thin tubular glass condensers joined in series have often been employed.

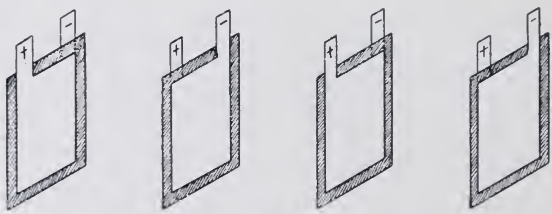


FIG. 62.—Diagram showing the Mode of arranging the Coatings of Condenser Plates.

Moscicki has suggested the use of glass tubes made thicker at the ends than in the middle, and coated within and without with a deposited silver film in the middle portion as a method of making condensers. (See *Engineering*, December 20, 1904, p. 865.)

An account of Moscicki's work will be found in *L'Éclairage Électrique* for October, 1904 (vol. 41, p. 14); and also in the *Electrotechnische Zeitschrift*, Nos. 25 and 26, June 23 and 30, 1904. He came to the conclusion, as the author and others had done long previously, that glass was the most suitable dielectric for high-pressure condensers, and he employed it in the form of glass tubes 0·5 mm. thick; but these tubes were thickened up at the ends, as otherwise he found they were perforated at the edges of the coatings by a voltage which the central portions of the glass could easily sustain. These glass tubes are coated with tinfoil or silver by deposit, the foil being put on with turpentine and air-bubbles carefully excluded.

A condenser for a power of 0·5 kilovolt amperes is made with five tubes of glass of which the diameter is 3 cms. and the thickness of wall 0·5 mm. These are contained in a cylinder of glass 47 cms. high and 9 cms. in diameter. The total weight varies from 3 to 3·5 kilogs. (7 to 8 lbs.). Such condensers will stand a working

pressure of 20,000 volts. It is claimed for these cylindrical condensers that they can be operated at a higher voltage per millimetre of thickness of the glass than flat plate condensers, and do not fail or heat on continuous working, and that with an alternating current having a frequency of 50~ the dielectric loss or loss by surface discharge does not exceed 1 per cent. of the energy-storing capacity.

It is well known that in the absence of flaws a plate condenser or Leyden jar is most usually punctured by the electric strain at some place near the edge of the tinfoil where the electric density is greatest. Moscicki states that a glass condenser plate is more easily punctured at the edges of the tinfoil when it is immersed in insulating oil.

In the latest form the Moscicki condenser is a sort of narrow glass bottle with the neck thicker than the bulb (see Fig. 63). This is coated within and without with a chemically deposited film of silver overlaid with copper. The inner layer is connected to a well-insulated terminal. This tube is enclosed in a water-tight metal tube, and the inner space filled in with glycerine and water. This acts as a cooling agent and makes perfect contact between the outer metal case and the outer silver coating of the jar. Such tubes are then assembled in batteries of any required capacity (see Fig. 64). They are all tested to a very much higher voltage than that at which they are to be used.

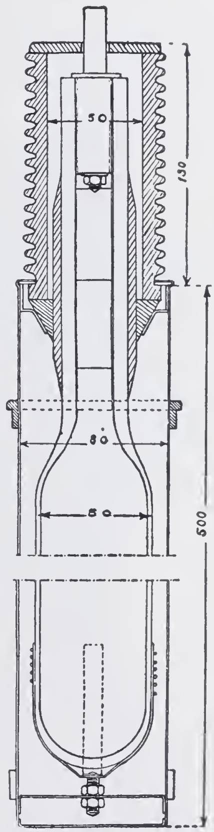


Fig. 63.—Section of Moscicki Condenser.

For the construction of condensers intended for very high pressures, micanite sheets, $\frac{1}{10}$ inch or 2·5 mms. in thickness, may be employed as the dielectric. To these sheets of tinfoil 1 inch smaller each way may be affixed by means of shellac varnish, and the coated plates immersed in a stoneware or ebonite box, filled with double-boiled linseed oil. As this oil does not dissolve shellac, a wooden box, well coated in the interior and with all joints covered with shellaced paper, may be employed to hold the oil.

For quantitative purposes, condensers constructed of metal plates placed in paraffin oil are to be preferred, since the dielectric constant of paraffin oil is not like that of glass, a function of the frequency (see Chap. II.). If ebonite is used as the dielectric the difficulty is to make the tinfoil stick to the ebonite. The adhesive called siccotine, or else indiarubber solution, may be employed for this purpose. The author has, however, found that a better plan is to cut sheets of ordinary tin-plate in pairs with right- and left-handed lugs, and pile these together with sheets of ebonite interposed on the plan just described for making a glass-plate condenser. The pile of condenser plates must be strongly

compressed, bound together with silk tape and immersed in insulating oil.

In some cases condensers of adjustable capacity are required. If only small capacities are required, this may be provided in the form of an air condenser with flat plates, which can be moved to or from each other, or the plates may be immersed in some liquid dielectric, such as paraffin oil or turpentine.

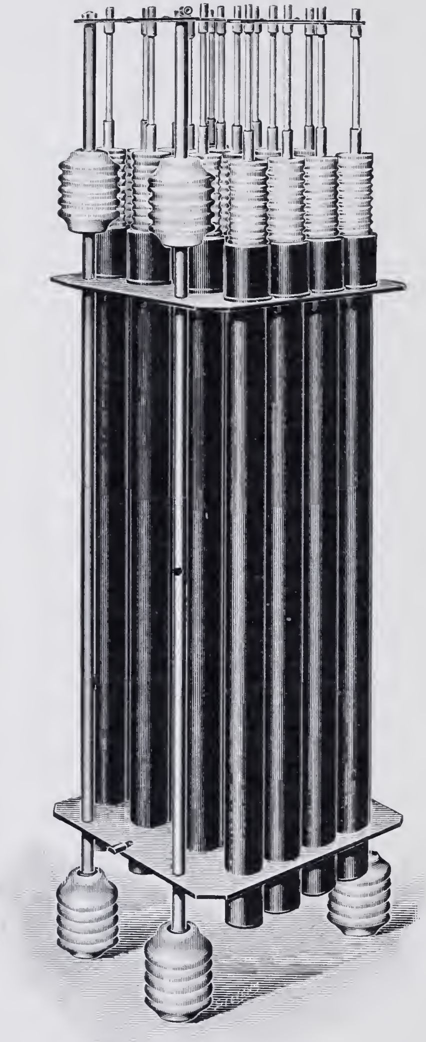


FIG. 64.—A Battery of Moscicki Condensers.

A convenient form of sliding condenser consists of a thin-walled cylinder of ebonite, closed at the bottom and lined within up to an inch of the top with a closely fitting cylinder of metal. The outside of the cylinder of ebonite is also covered with a closely fitting cylinder of metal, and the arrangement resembles that called a dissected Leyden jar. By drawing the outside cylinder more or less off the ebonite one, the capacity is reduced, and the capacity corresponding to various positions of the outer cylinder can be marked on the ebonite.

Another form of condenser of adjustable capacity, suitable, however, only for a small range of variation and for a small capacity, is made as follows:—

In an ebonite box are fitted a number of pairs of quadrant-shaped plates, one above the other. These resemble the fixed plates in a Kelvin multicellular electrostatic voltmeter. All these quadrant plates are connected together and to one terminal on the box. In the centre is a metal rod in pivot carrying a number of paddle-shaped metal plates which are spaced apart by the same distance as the fixed plates. The rod is so held that the plates on it are interspaced with the fixed plates. The box is filled with insulating oil.

When the movable plates are turned by the rod so as to be quite within the fixed plates, they form with these last a condenser of which the oil is the dielectric. When they are turned so as to be quite apart from the fixed plates, the capacity is greatly reduced. If the rod carries a pointer moving over a scale, the scale can be calibrated to show the capacity of the two sets of plates with respect to each other for any required positions of the movable plates. The rod is, of course, connected by some form of spring or bearing contact with the second terminal of the instrument (see Fig. 65).

In the construction or selection of condensers, especially those of large capacity for wireless telegraph purposes, we have to give due weight to various considerations. We have to consider questions of durability, energy dissipation, bulk, and cost. The ordinary Leyden jar is simple and not objectionable where small capacities alone are concerned, but its energy-storing capacity is small compared with its bulk, and its use is out of the question when large capacities such as 1 or 2 microfarads are concerned.

When large condensers have to be in continual use, the dielectric hysteresis becomes important, and also any tendency in the dielectric to "age" or become brittle by long use. Glass gives some trouble in this last respect. Ebonite is too costly to be used for large capacities, and micanite has too much dielectric hysteresis. Hence attention has been directed to the use of air as a dielectric.

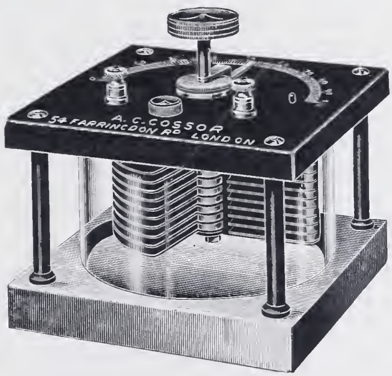


Fig. 65.—Variable Capacity Oil Condenser.

Owing to the relatively small dielectric strength of air at normal pressures, we are either obliged to use very large metal plates set far apart, or else to employ compressed air as the dielectric.

Since the dielectric strength of air at atmospheric pressure is very nearly 38,000 volts per centimetre (see Chap. II. § 6), and since a factor of safety of at least 5 or 6 should be used to avoid considerable energy loss by brush discharge, it is seen that if we wish to work an air condenser at a voltage of 100,000 volts, the plates must be at least 20 cms. apart. It will be shown in the next chapter that the capacity in microfarads of a parallel plate condenser of which the plate diameter is large compared with their distance apart can be approximately calculated by the formula—

$$\textit{capacity in microfarads} = \frac{\textit{surface of plate in square centimetres}}{4\pi \times 9 \times 10^5 \times d}$$

where d is the distance of the parallel plates in centimetres. If, then, $d = 20$ cms., we should require a total positive or negative plate surface of nearly 226 million square cms., or 22,600 square metres, to obtain a capacity of 1 mfd. This means that two square

plates, each having a side 150 metres, or nearly 500 feet, placed 20 cms., or nearly 8 inches, apart in air at ordinary pressure, would have a capacity of 1 mfd., and would stand charging to a pressure of 100,000 or even 300,000 volts without sparking across. At 100,000 volts this condenser would store up 5000 joules of energy, or nearly 4000 foot-pounds, and would have a bulk of nearly 170,000 cubic feet. This is at the rate of 40 cubic feet per foot-pound of stored energy. A glass-plate condenser for the same capacity and voltage would not occupy one-hundredth part of the above volume.

The use of compressed air, however, presents some advantages.

The dielectric strength increases almost proportionately to the pressure. Hence if, instead of employing air at atmospheric pressure as the dielectric, we compress it to 140 pounds on the square inch, it attains a dielectric strength far greater than that of glass. Also the dielectric constant is slightly increased.

Moreover, as R. A. Fessenden has shown, brush discharges are at high air pressures almost abolished. Accordingly an air condenser can be advantageously constructed with compressed air as dielectric.

Metal plates kept at a small distance apart are enclosed in a strong iron vessel in which air can be compressed under 10 or 12 atmospheres. Thus Fessenden states (see U.S.A. Patent, No. 793,777, applied for March 30, 1905, or *The Electrician*, 1905, vol. 55, p. 795) that in air at 175 pounds pressure per square inch metal plates 0·083 inch apart will withstand without sparking a voltage of 27,500 volts. At this rate an air condenser of 1 mfd. capacity to stand 100,000 volts could be contained in a space of 500 cubic feet, and would not exhibit energy loss by electric brush discharge or dielectric hysteresis to any sensible degree. It seems evident that the use of compressed air, or, better still, compressed nitrogen or carbonic dioxide, as a dielectric for condensers will be found to possess many advantages in constructing high voltage condensers at reasonable cost for wireless telegraph power stations. In large radiotelegraphic stations, where space can be obtained, air condensers consisting of plates of metal suspended in the atmosphere several inches apart have been employed, as mentioned, in a later chapter.

12. Oscillation Transformers.—An essential part of the arrangements for producing trains of electric oscillations by condenser discharge is the inductive circuit which is placed in series with the condenser. This most frequently consists of one circuit of an air core transformer which is called an *oscillation transformer*.

Two circuits are associated together inductively by being wound over one another on some support, but at the same time well insulated from each other. One of these is called the primary and the other the secondary circuit. The primary circuit is placed in series with the condenser and the spark ball discharger, this constituting the circuit in which electric oscillations are set up by the discharge of the condenser. These oscillations induce other oscillations called secondary oscillations in the secondary circuit of the oscillation transformer, and if the secondary circuit has a larger number of turns than the primary circuit, the potential difference at the extremities of the circuit of the oscillation transformer will be greater than at the terminals of the primary circuit in a certain ratio.

The form which this oscillation transformer takes is dependent upon the purposes to which the apparatus is to be applied. One well-known form of oscillation transformer is called a Tesla Coil, and a description of this coil was given by Mr. Nikola Tesla in a lecture delivered some years ago before the Royal Institution in London (in February, 1892) as follows [31] :—

"The coil consists of two spools of hard rubber, R, R (see Fig. 66), held apart at

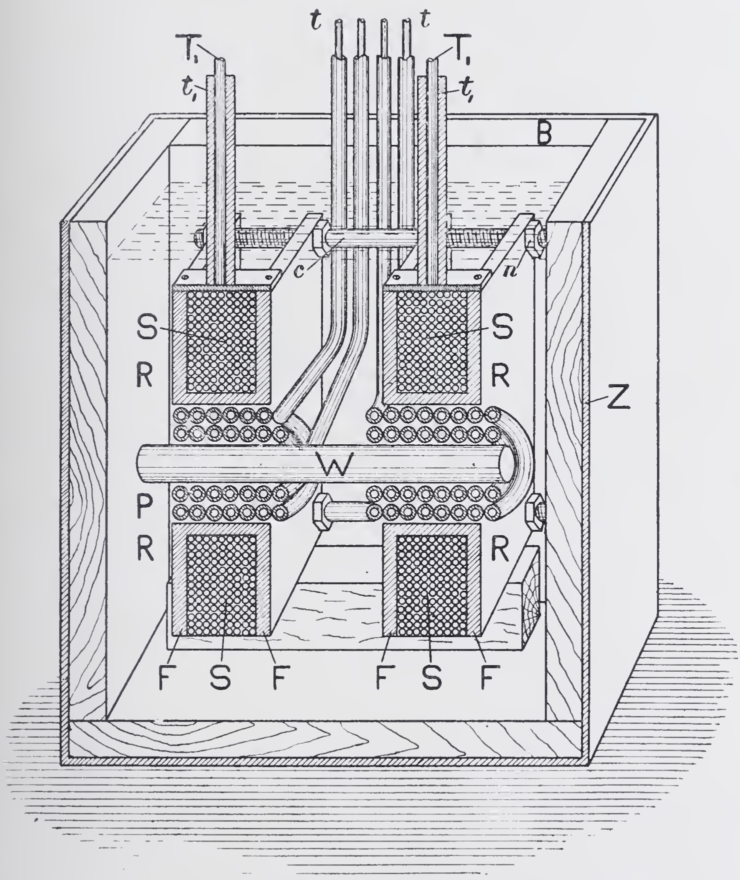


Fig. 66.—Tesla Oscillation Transformer. (*Sectional view.*)

a distance of 10 cms. by bolts, *c*, and nuts, *n*, likewise of hard rubber. Each spool comprises a tube, T, of approximately 8 cms. inside diameter and 3 mms. thick, upon which are screwed two flanges, F, F, 24 cms. square. The secondary, S, S, of the best guttapercha-covered wire, has 26 layers, 10 turns in each, giving for each half a total of 260 turns. The two halves are wound oppositely and connected in series, the connection between both being made over the primary. This disposition,

[31] See Nikola Tesla, "Experiments with Alternate Currents of High Potential and High Frequency," *Journal of the Institution of Electrical Engineers*, 1892, vol. xxi. p. 62.

besides being convenient, has the advantage that when the coil is well balanced—that is, when both of its terminals, T_1, T_1, are connected to bodies or devices of equal capacity—there is not much danger of breaking through to the primary, and the insulation between the primary and the secondary need not be thick. In using the coil, it is advisable to attach to *both* terminals devices of nearly equal capacity, as, when the capacity of the terminals is not equal, sparks will be apt to pass to the primary. To avoid this, the middle point of the secondary may be connected to the primary, but this is not always practicable.

"The primary P, P is wound in two parts, and oppositely, upon a wooden spool, W, and the four ends are led out of the oil through hard rubber tubes, *t*, *t*. The ends of the secondary T_1 T_1 are also led out of the oil through rubber tubes, t_1, t_1, of great thickness. The primary and secondary layers are insulated by cotton cloth, the thickness of the insulation, of course, bearing some proportion to the difference of potential between the turns of the different layers. Each half of the primary has four layers, 24 turns in each, this giving a total of 96 turns. When both the parts are connected in series, this gives a ratio of conversion of about 1 : 2·7, and with the primaries in multiple 1 : 5·4; but in operating with very rapidly alternating currents, this ratio does not convey even an approximate idea of the ratio of the E.M.F.'s in the primary and secondary circuits."

The coil is placed in a wood or ebonite box, which is filled with double-boiled linseed oil or highly insulating resin oil, or else with ordinary fluid high flash-point paraffin oil, and the coil when in place must be entirely covered by the oil. The coil is held in position in the oil on wooden supports, there being about 5 cms. thickness of oil all round. Where the oil is not specially needed, the space is filled with pieces of wood, and for this purpose principally the wooden box B surrounding the whole is used.

In oscillation transformers in which the primary circuit is traversed by the discharge of a condenser and a secondary circuit is inductively associated with it, this latter, if in many turns, becomes the seat of very high electromotive forces. In fact, differences of potential amounting to many hundreds of volts may exist between adjacent turns of the secondary. Hence, very good insulation is required, and it has been found that no form of secondary winding in which layers of wire are wound over one another or in which the different turns of the wire are in close contact will very long withstand the electric strain without failure of insulation.

Hence one great principle in the construction of a high potential high frequency induction coil or oscillation transformer is to wind the primary and secondary circuit in single layers, the turns not touching.

This may be achieved in the following manner. The primary circuit consists of a spiral of bare copper wire, 3 or 4 mms. in diameter, the spiral consisting, say, of 20 turns wound open fashion round a mandril 7 or 8 cms. in diameter. Within this spiral is placed an ebonite or glass tube, the walls of which are at least 3 mms. thick and the length 25 cms. or so. On this glass or ebonite tube is wound in one single layer a much finer silk-covered wire, say, No. 26 S.W.G. size = 0·457 mm. diameter. The turns of this wire are prevented from touching each other by winding a paraffined silk thread in between them, or by winding the wire in a groove turned in the cylinder. This bobbin may be placed in a glass or ebonite box full of double-boiled linseed oil or vaseline oil free from water. The coil must be entirely immersed, and the ends of the primary and secondary wires must be brought out through glass or ebonite tubes which have their lower ends well under the oil.

When oscillatory discharges from a condenser or Leyden jar are passed through the thick spiral, we have long sparks or high potential high frequency discharges from the secondary circuit.

The following is a detailed description which has been given by Professor Elihu Thomson of two oscillation transformers of the above kind. One suitable for creating 30-inch sparks was made as follows [32] :—

The primary consisted of 10 turns of wire, made up of two No. 6 copper wires wound on a wooden frame. The wires were wound side by side in notches. This coil or mandril was 18 inches long and 15·5 inches in diameter. Its resistance was 0·0088 ohm and inductance 0·0076 millihenry.

The secondary consisted of 396 turns of insulated wire, No. 26 B. and S. gauge, wound as a single layer in notches on an ebonite frame, the wire turns being spaced apart so as to form a coil 18 inches in length. The diameter of the secondary was 12 inches, and it was placed inside the primary. The total length of secondary wire was 1250 feet and weight one pound. The resistance was 41·6 ohms and inductance 25·2 millihenrys. These coils were immersed and supported concentrically in a vat of oil, and the secondary had its terminals carried out through glass tubes to spark balls.

Two condensers were provided for creating the primary discharges. They consisted of two boxes, each 7 inches by 15½ inches inside and 17½ inches deep. Each box contained 84 built-up mica sheets, 15 inches square and 0·075 inch thick; 42 of these were coated with tinfoil 10 inches by 11 inches in area. The effective coated surface of each plate was 110 inches, and the total surface 4510 square inches. The capacity of each condenser was 0·03 mfd. Hence the two boxes afforded a total capacity of 0·06 mfd. When these condensers were charged from the high-tension terminals of an alternating current transformer at a pressure of 20,000 volts, and discharged across an air gap through the primary circuit of the above-described oscillation transformer, oscillatory high frequency sparks 30 inches in length passed between the terminals of the secondary circuit.

An oscillation transformer giving 64-inch sparks was made as follows :—

The primary coil consisted of 15 turns of double No. 6 S.W.G. copper wire, the length being 85 feet of wire double wound in an open coil 28 inches in length and 22 inches in diameter. The resistance of this primary circuit was 0·0147 ohm and inductance 0·09 of a millihenry.

The secondary bobbin was 28 inches long and 17 inches in diameter, and was placed inside the primary coil. The wire was No. 26 S.W.G. size, about 2·25 lbs. in weight and 2600 feet in length, and wound in notches on an ebonite frame in 580 turns.

The associated condenser consisted of mica plates covered with tinfoil and arranged in oil in a box. Three such boxes were used, each having a capacity of 0·015 mfd., and having therefore a total capacity of 0·045 mfd. These were charged by an alternating current transformer having a voltage of 30,000, and discharged through the

[32] See Elihu Thomson, "On Apparatus for obtaining High Frequencies and Pressures," *The Electrician*, November 3, 1899, vol. 44, p. 40.

primary of the above-described coil across an air gap. A blast of air was kept blowing on the gaps during discharge to destroy the arc.

In some cases the use of vats of oil is objectionable, hence for moderate spark lengths it is desirable to dispense with oil insulation. In this case the secondary circuit must be wound on one layer on a glass or ebonite tube. If guttapercha-covered wire is used, it must be covered with a layer of well-shellaced tape to protect it from the action of light and air. This ebonite tube may be placed inside another tube, on the outside of which the primary coil is wound in a few open turns, or the primary may be placed inside the glass or ebonite tube on which the secondary is wound. In any case

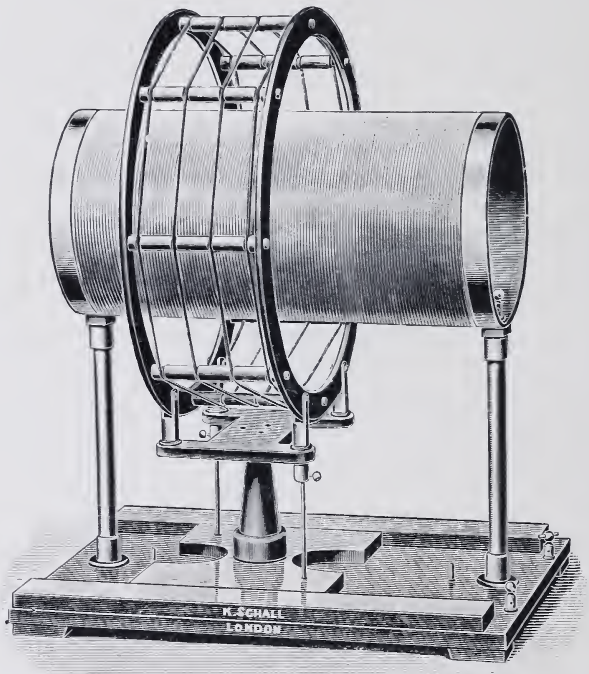


Fig. 67.—Oscillation Transformer, Primary and Secondary loosely coupled.

the ends of the secondary circuit must be brought out at opposite ends of the tube in which or on which it is wound. In other cases the primary circuit forms a few open turns of much larger diameter than the secondary circuit (see Fig. 67). This last form is described as the "loose coupling" of the primary and secondary circuit, whereas when the primary and secondary are in close contact the arrangement is called "close coupling."

In any case the primary circuit should consist of a few turns of wire as openly spaced as possible, for the sake of making the inductance low.

Nothing is gained by using a primary current of many close turns, because the increase of inductive effect on the secondary, due to an

increase in the number of primary turns, is almost exactly annulled by the decreased current through the primary, due to its own greater inductance. This matter will be considered more in detail in the next chapter.

Marconi devised for wireless telegraph purposes a form of oscillation transformer in which the two circuits are of heavily insulated wire, and are wound over one another on a square or round wooden frame. The primary circuit consists of one or a few turns of a number of wires in parallel, and the secondary circuit of a few turns of wire in series.

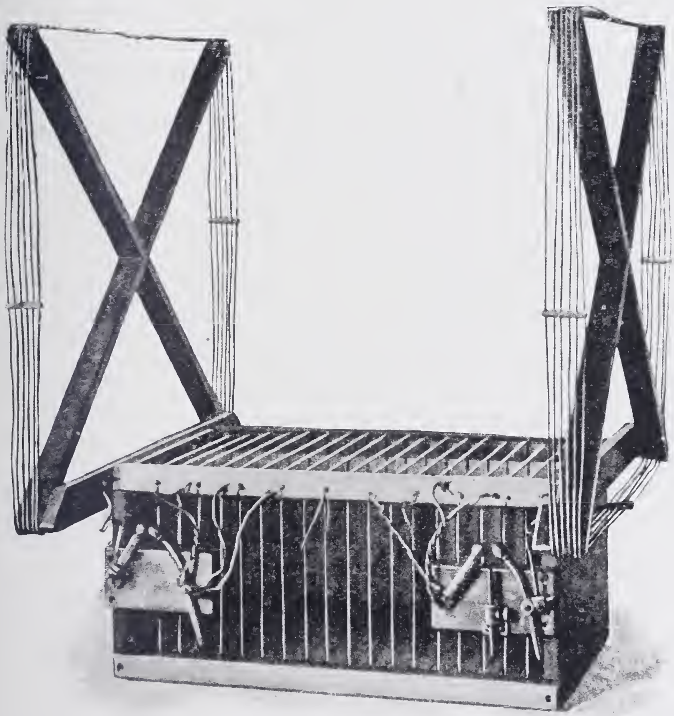


FIG. 68.—Oscillation Transformer, with Primary and Secondary Coils widely separated.

In some cases where very loose coupling is required the primary and secondary circuits may consist of insulated wire wound on two square frames, the primary on one and the secondary on the other, and these frames may be placed a considerable distance apart (see Fig. 68).

The full theory of oscillation transformers cannot be given until the subject of electric resonance has been considered, but meanwhile it will be sufficient to caution the reader that the ratio in which a high frequency oscillation transformer transforms electric pressure is by no means in the ratio of the number of turns. The oscillation

transformer must in some of its forms be considered as a transformer with very large magnetic leakage, hence only a small portion of the magnetic flux created by the primary circuit is linked with the secondary circuit.

In the chapter on wireless telegraphy receivers, we shall consider the structure of certain peculiar forms of oscillation transformer which have been found to be of use in transforming the extra high frequency oscillations produced in wires by the impact on them of electric waves.

13. General Arrangement of Apparatus for producing Electric Oscillations by means of Condenser Discharges. Arc-stoppers and Dischargers.—Having considered the principal pieces of apparatus in detail, we may next discuss the general arrangements convenient for certain classes of work in connection with the production of trains of damped electric oscillations and electric waves.

When no very great power is required, say an expenditure up to 150 watts or so, the most simple and easily managed arrangement is a 10-inch induction coil worked off secondary cells, actuated either by a motor-driven mercury break or else an automatic hammer break. Since the above coil requires 10 amperes at 16 volts to work it well, it is best to work it with 8 to 10 storage cells, capable of giving 10 amperes for 4 or 5 hours. These cells are now made up in sets of 4 or 6 in celluloid boxes contained in a teak case. There should be a double pole cut out or fuze wire inserted between the battery and coil, and also a double pole switch, so that if the hammer break sticks the cells will not be overworked. These cells can be charged from any continuous current lighting circuit through resistances or lamps

The condenser attached to the secondary terminals of the coil may consist of Leyden jars or an ebonite or glass-plate condenser in oil.

The variable inductance used in series with it may be of the pattern shown in Fig. 12, § 5, of Chapter II. A special spark discharger with balls adjustable for distance by a fine screw is very convenient, and this should be contained in a wooden or metal box, so as to shut in the light of the spark and reduce the noise. The circuit of the condenser may also contain a Tesla coil or oscillation transformer, and we can then draw from the terminals of this coil high frequency high potential discharges, sparks or brushes. An apparatus of this kind is much used for electro-medical work.

When a more powerful plant is required, then an alternating current transformer must be employed. This may be of any size from $\frac{1}{2}$ kw. output upwards. A convenient size is a 2-kw. transformer, raising pressure from 140 to 20,000 volts, adapted for a frequency of 50. Associated with this is a motor-generator consisting of a four-pole continuous current motor with Gramme ring armature and slip rings on the shaft, as described in § 9 of this chapter. This machine may be of 3-kw. size, and if wound for 200 volts on the continuous current side and a speed of 1500 R.P.M., will give alternating current at a frequency of 50 and a voltage of 140 on the slip rings.

If a continuous current supply is not available to drive such a motor generator, then a small oil engine may be coupled to it to drive it, or else a suitable small alternator may be put in its place as already described.

In those cases in which larger powers still are required, a plant consisting of an oil or steam engine driving directly or by a belt an alternator giving alternating current at 2000 volts may be arranged. The pressure of the current is then raised by transformers to 20,000 or 30,000 volts. In this case the transformers should be oil-insulated transformers.

When low resistance transformers of large size are employed to charge condensers, it is necessary to destroy the alternating current arc which tends to form across the spark balls and so stops the production of oscillations.

This may best be accomplished by means of a plan devised by the author.[33] In the primary circuit of the transformer T (see Fig. 69) are placed two choking coils, H_1, H_2, or inductances in series, each consisting of a long bobbin of wire standing on an insulated wooden slab. An iron core for each coil, E_1 and E_2, is provided, made of thin sheet-iron stampings like a transformer core, and it is in the shape of a letter E (see Fig. 69). If this E-shaped iron is let down into the

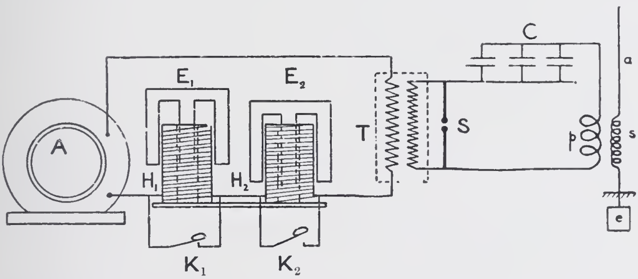


FIG. 69.—Arrangement of Apparatus for producing Powerful Electric Oscillations. (Fleming.) A, alternator; T, transformer; H_1, H_2, choking coils; C, condenser; p, s, oscillation transformer.

coil it gives it a greatly increased inductance. In the wooden base there is a transverse piece of laminated iron which completes the magnetic circuit when the core is let right down. Two such choking coils are joined in series with each other and with the primary circuit of the transformer T. These choking coils can be short circuited by keys, K_1 and K_2. The alternator A is run at a speed required to give the necessary normal primary current of the transformer, and both iron cores are let down into the choking coils. Then the secondary circuit of the transformer T is short circuited, and also one of the choking coils H_2, by its appropriate key, K_2, and furthermore the core of the other choking coil H_1 is raised until the current flowing through it is not more than the full load current of the transformer T. In the next place the secondary terminals of the high-tension transformer are connected to a pair of spark balls, S, and to a condenser, C, and inductance in p series, which last may consist of the primary circuit of an oscillation transformer, ps, of any form.

If then the key K_2 is raised, and if the spark balls are adjusted at

[33] See British Patent Specification, No. 3481 of 1901, application of February 18, 1901; also United States Patent Specification, No. 758,004, application of April 8, 1901.

the proper distance, it will be found that no spark passes when the short circuit key of the choker is up, but that a condenser discharge takes place when the key is depressed. The reason for this is that when both choking coils are operative the impedance is so great that no current can flow through them sufficient to create much secondary voltage in the high-tension transformer. If, however, one choker is short circuited, then the impedance is so far reduced that the transformer receives current enough to create a secondary voltage. By adjusting the length of the spark gap and the position of the core of one of the chokers, it is possible to make this spark consist wholly of an oscillatory discharge of the condenser, and not have superimposed upon it any alternating current arc discharge directly due to the transformer. If this arc discharge is not suppressed there will be no true oscillatory discharge in the condenser circuit or only a feeble one.

The reason for this is obvious. As long as the arc discharge continues, the secondary terminals of the transformer are reduced to nearly the same potential, or at most differ by a few hundred volts. It is not until the arc is stopped that the spark balls come up to a sufficient potential difference to give a fresh charge to the condenser, and by creating a discharge across the gap start into existence a fresh train of oscillations.

Various other plans have been suggested for destroying the arc discharge whilst permitting the condenser discharge to take place.

Tesla employed a powerful magnet placed with the direction of its magnet interpolar field transverse to the line joining the spark balls. The pointed field poles were covered with some non-conducting and non-inflammable material, such as mica or porcelain. This strong magnetic field blows out the arc just as in the ordinary electric tram-car controller. Another plan, due to Elihu Thomson, is to employ a powerful jet of air. The air blast is applied just between the spark balls, and blows away the arc but not the condenser spark.

A third plan, proposed by M. D'Arsonval, is to construct the discharger with the spark balls at the extremities of metallic arms. One of these is made to revolve at a high speed. Hence the arc, if formed, is broken as the balls separate. The condenser is then again charged, and discharges again as the balls pass each other, but the electric arc which forms at that instant is again destroyed as the balls move apart. A somewhat similar arrangement has been described by Robert Grison. A shaft has on it four arms of metal each ending in a ball. It is caused to revolve so that the balls at the arm extremities pass in their revolution between two other fixed balls, but just not touching them. The condenser in series with these two last balls is then discharged four times every revolution, but the arc which attempts to follow is at once extinguished. A fourth plan is to employ a transformer, as made by Leslie Miller, with large magnetic leakage. Hence, as soon as the condenser is charged and discharges, and the true arc discharge created, the current given out by the secondary circuit of the transformer is greatly increased. This, owing to the construction of the transformer, causes so large a fall in potential between the terminals that the arc can no longer be maintained.

This extinction of the alternating current arc is facilitated by the employment of curved metallic horns instead of spark balls.

It is well known that if an alternating current arc is formed between such horns, the arc tends to rise up to the wider part of the gap. In so doing it gets stretched out and extinguished, and the process is assisted by the upward draught of air caused by the arc, and this can be furthermore helped by putting a non-conducting porcelain or stoneware chimney over the horns to help the draught action.

When employing only small powers, the spark discharger consists usually of two brass balls, 1 or 2 cms. in diameter, their distance being adjustable. The ordinary sliding rods terminated in brass balls, which are placed on induction coil secondary terminals, are quite suitable as a discharger for many experiments, and even for wireless telegraphy. For larger powers, balls of some more refractory material, such as cast iron, are better.

The distance of these discharge surfaces must be capable of accurate adjustment by means of a screw. As the noise of the oscillatory spark is very distressing when large powers are being

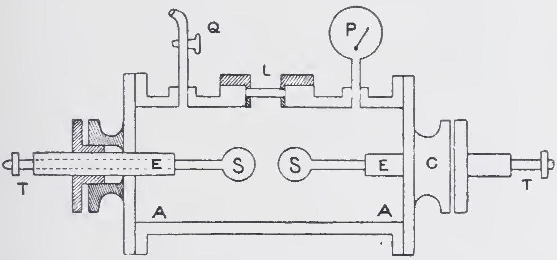


Fig. 70.—Silent Discharger. (Fleming.) S, S, spark balls ; A, A, cast-iron case ; L, peep hole ; P, pressure gauge ; Q, air-pipe.

employed, the author has devised a plan by which the discharger is contained in a cast-iron case with thick walls. A peep-hole glazed with thick plate glass is provided, and also stuffing boxes or glands, through which are passed ebonite rods pierced with metal rods, by which the discharge is conveyed to balls fixed on the ends of the rods. The diagram in Fig. 70 shows such a silent discharger.

The discharger will only be silent if the iron case has very thick walls and is closed perfectly air-tight. It may also be arranged to contain compressed carbonic acid gas or nitrogen. If the spark is taken in compressed air or other gases, the spark length for any given voltage is almost inversely as the total pressure. Further reference to this matter is made in the next chapter.

One difficulty which presents itself when the spark is taken in a closed vessel full of air is the chemical production of oxides of nitrogen by the discharge. These vapours, being acid, cause a loss of insulation by condensing on the insulating supports. The difficulty is only slightly overcome by placing quicklime or caustic potash in the interior. A better plan is to fill the vessel once for all with nitrogen gas.

This can be prepared sufficiently pure for this purpose by burning pieces of phosphorus under a glass bell jar standing over water. When the phosphoric pentoxide produced has dissolved, the residual gas can be pumped into the spark-ball chamber, provided that the air has previously been exhausted from it. When once the spark box has been filled with nitrogen, it will not, if air-tight, require further attention for some time, and no production of oxides of nitrogen can take place.

Since the apparent dielectric strength of air and other gases is greater for thin layers than for thick ones, whilst the spark resistance per unit of length is less, it is in some cases desirable to employ multiple spark gaps, that is, a series of discharge balls, so that the spark is cut up into several sparks. These can be arranged in a box, and their distances adjusted by a screw on a plan suggested by J. S. Stone (see Fig. 71). (See United States Patent, No. 768,000, applied for February 23, 1904.)

Since the spark balls wear away with the discharge, it is necessary to make some arrangement for turning them round, so as to bring fresh surfaces continually in apposition.

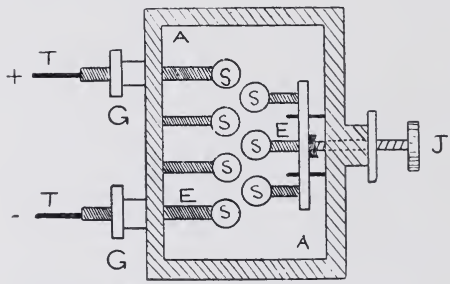


FIG. 71.—Multiple Ball Discharger. (J. S. Stone.)

The author has devised a special form of enclosed discharger with rotating balls, which can be worked in compressed gases. The detailed description of this discharger is given in a later chapter of this treatise.

In all experimental work in which an induction coil or transformer is employed to charge a condenser, subsequently discharged across a spark gap to produce damped oscillations, it is a great advantage to keep a steady blast of air impinging upon the balls and the gaps between them. Even with an induction coil there is a certain amount of arcing between the balls, that is to say, the discharge which takes place between them is not wholly due to energy coming out of the condenser, but is partly due to energy coming directly from the coil secondary circuit which takes the form of an arc.

The air blast extinguishes this arc as soon as it is formed, and it also keeps the balls cool and so maintains at its highest value the spark potential difference corresponding to a given spark gap length. The blast of air can be conveniently provided by a Lennox blower, or rotary fan driven by a small electric motor, which can be actuated by any ordinary electric supply service. An air blast equal to a pressure of 16 or 20 inches of water can be thus obtained, and this is allowed to impinge on the air gap by means of a glass jet. In the case of larger transformer plants a higher air pressure is necessary to quench the arc. In all quantitative experiments an air blast thus used greatly assists in keeping the discharge current constant. We

shall further discuss the action of dischargers and various types of them in a later chapter when dealing with radiotelegraphic stations, and the reader is particularly referred to Chap. VIII. § 16, for a description of Mr. Marconi's high-speed rotating dischargers for long-distance radiotelegraphy.

14. The Production of Undamped or Persistent Electric Oscillations.—In connection with investigations on high frequency electric currents and electric oscillations, it was very early recognized that some means was required for producing undamped or persistent oscillations of a much higher frequency than those which can be conveniently and easily generated by high frequency alternators. Remarkable discoveries in connection with the continuous current electric arc, have, however, provided one solution of the problem, and enabled us to produce undamped oscillations of a frequency and amplitude useful in radiotelegraphy.

They have at the same time given the means for accomplishing the important feat of transmitting not merely signals, but articulate

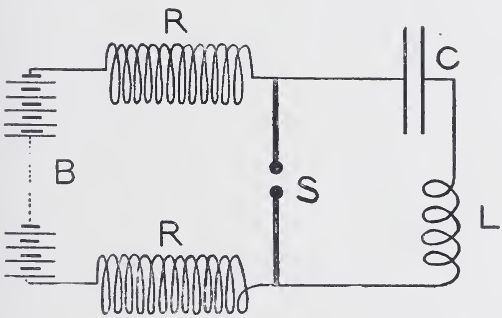


FIG. 72.—Elihu Thomson's Method for the Production of Continuous Trains of Electric Oscillations. B, battery; R, R, inductive resistances; S, spark balls; C, condenser; L, inductance.

speech by means of electric waves to a distance. A point of departure in this matter is a United States Patent Specification, No. 500,630, July 18, 1892, filed by Professor Elihu Thomson, describing a method for the production of undamped or persistent electric oscillations by the following means. One or two coils of large inductance, R (see Fig. 72), are placed in series with a spark gap across continuous current mains, and the spark gap, S, is shunted by a condenser, C, in series with another inductive circuit, L, which may be the primary coil of a high frequency transformer.

The continuous voltage may be supplied by a storage battery, B, or by a dynamo, but should be about 500 volts or more.

An air blast or magnetic field must be used to extinguish the continuous current arc.

The ninth claim of the specification reads as follows:—

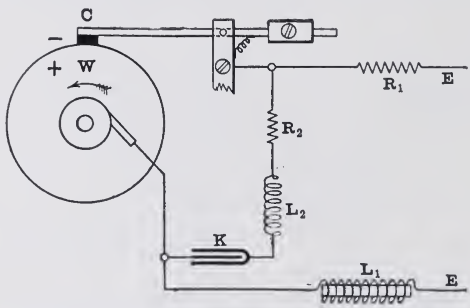
"The method of obtaining from continuous currents or currents tending through self-induction or otherwise to remain unchanged or resist sudden changes of value, high frequency alternating currents of desired periodicity, consisting in bridging by determinate capacity of condenser and a determinate

self-induction coil or circuit a spark gap in said continuous current circuit, said spark gap being adjusted and arranged so as to respond to the desired frequency substantially as set forth."

In the above specification nothing is, however, said about the employment of a carbon arc instead of a spark gap, but Professor Elihu Thomson has informed the author he had observed the effect.

It is somewhat doubtful whether this particular arrangement did or can produce true undamped persistent oscillations. No proof of this was given in the specification. The only way in which it can be proved that any oscillations are persistent, is by causing them to induce high voltage oscillations of the same frequency in a secondary circuit containing a spark gap, and then examining the image of this induced spark in a rapidly revolving mirror. If the oscillations are persistent the image will be drawn out into an unbroken band of light.

In the absence of such evidence we cannot conclude that the oscillations given by Elihu Thomson's method are truly persistent, but at any rate credit should be given to him for an appreciation of the fact that a continuous electric current could be partly converted into high frequency oscillations by means of a condenser and inductance shunted across an arc or spark produced by a continuous current.[34]



[*Reproduced by permission from "The Electrician."*]

FIG. 73.

At a later date, in 1906, Mr. S. G. Brown devised an arrangement somewhat similar, which also was claimed, though no proof was given, to produce undamped or persistent oscillations.[35]

The arrangement was as follows :—

A disc of metal, W (see Fig. 73), preferably of aluminium, is fixed to a shaft, and kept in slow rotation by an electric motor. Against the edge of this disc a copper block, C, rests pressing lightly, and a direct current under a pressure of about 200 volts is passed through a resistance R_1, and large inductance L_1, and across the loose contact between the block and the disc. A condenser K, and small inductance, L_2, in series are also joined as a shunt between the block and the disc. When the direct current passes, oscillations of high frequency are set up in this condenser circuit, and these can be transformed up or down by an oscillation transformer. We cannot conclude, however, without proof that this method produces continuous oscillations, and not a very rapid series of intermittent

[34] For a confirmation of this see the remarks made subsequently, in 1899, by Prof. Elihu Thomson in an address to the American Association for the Advancement of Science. *The Electrician*, September 22, 1899, vol. 43, p. 778. "The Field of Experimental Research."

[35] See S. G. Brown, *The Electrician*, vol. 58, p. 201, 1906, "On a Method of producing Continuous High Frequency Electric Oscillations.

oscillations. The only convincing evidence that any method provides the means for the production of truly persistent undamped oscillations is afforded when an actual measurement of the logarithmic decrement shows it to have a zero value, and this has not been done either for Elihu Thomson's or for Brown's method.

In 1900 Mr. W. Duddell read an interesting paper before the Institution of Electrical Engineers of London in which he showed that if a condenser of suitable capacity and an inductance are connected in series with their terminals attached to the carbons of a continuous current arc of certain length and current formed with *solid* carbons, the arc gives forth a musical note of high pitch.[36]

Hence an arc so shunted has from that time been called a *musical arc*.

The pitch of this note was found to vary with the capacity and inductance in the shunt, but these have to be both moderately large to bring the note within audible limits.

The same creation of oscillations in a condenser and inductive circuit is also observed in the case of a metallic arc, that is, an electric arc produced between metallic rods. By means of high tension continuous current producing arc discharges between metallic surfaces in vacuum, MM. Simon and Reich state that they have been able to produce extremely strong oscillations in a condenser placed in an inductive shunt circuit connecting the two surfaces between which the arc discharge takes place.[37]

Mr. Duddell has given the following data for an open and enclosed carbon arc, which will serve as a guide in selecting a suitable capacity and inductance for producing the musical arc.

Data for the Production of Musical Arcs.

	Open arc.	Enclosed arc.
Carbons, both solid	Conradty carbons	Electra carbons
Diameter of carbons	9 mm.	13 mm.
Arc length	1·5 mm.	1 mm.
Arc current	3·5 amps.	5 amps.
Resistance in series with the arc	42 ohms	28 ohms
Induction of shunt across carbons	5·3 millihenrys	5·3 millihenrys
Resistance of shunt	0·41 ohm	0·41 ohm
Capacity of condenser	1·1 to 5·4 mfds.	1·1 to 5·4 mfds.
R.M.S. value of current through condenser	3 amps.	4·5 amps.

The production of this effect is, however, subject to certain conditions. The arc A must be formed by the electromotive force of a secondary battery or other steady generator, and a resistance, R (see Fig. 74), must be placed in series with it. The inductive resistance L placed a shunt to the arc must be a low resistance—generally speaking, something less than 1 ohm. The condenser C employed should be one suitable for high potential, as although the impressed electromotive force on it is only 50 volts, the action of resonance (see Chap. III.) creates a potential difference between its plates, which at

[36] See W. Duddell, "On Rapid Variations in the Current through the Direct-current Arc," *Journal of the Institution of Electrical Engineers*, 1900, vol. 30, p. 232. See also British Patent Specification, W. Duddell, No. 21,629 of 1900.

[37] See *La Revue Practique de l'Électricité*, April 20, 1904.

moments rises to several hundred volts, and hence a thin paper condenser may break down.

One explanation put forward as an explanation of this effect on its discovery was that it essentially depends upon the existence of a *negative resistance* in the arc, and that the frequency which can be obtained is limited by the arc itself. We shall present the outlines of this theory first, as proposed by Mr. Duddell and supported by some others.

Suppose a small instantaneous change, dV, is made in the potential difference of the electrodes, whether carbon or metal, between which the arc is formed, and let the corresponding small change in the current through the arc be denoted by dA. Also let the resistance of the inductance in series with the condenser be represented by r. The theory advocated by Mr. Duddell is that the

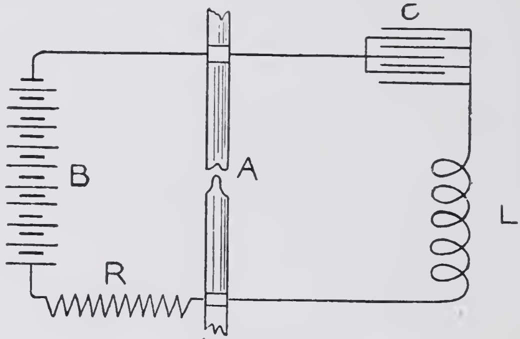


Fig. 74.—Arrangements for producing Duddell's Musical Arc. B, battery; R, resistance; A, carbon arc; C, condenser; L, inductance.

conditions for the production of high frequency alternating currents or oscillations in the condenser circuit are that $\frac{dV}{dA}$ must be negative in sign, and must be numerically greater than r. A negative value of $\frac{dV}{dA}$ implies that the current through the arc must vary in the opposite sense to the potential difference, that is, the current must increase as the potential difference decreases, and *vice versâ*. Messrs. Frith and Rogers have experimentally determined the value of $\frac{dV}{dA}$ (which they call the resistance of the electric arc) for various arcs made with cored and solid carbons, and they found that whilst $\frac{dV}{dA}$ was always positive for cored carbons, it was negative when *both* carbons were solid and was as small as -2 ohms for a 4-ampere arc between solid carbons.[38] As the resistance of the inductive coil in series with the condenser can easily be made less than 2 ohms, the two criteria can be satisfied.

[38] See *Proc. Phys. Soc. Lond.*, 1896, vol. xiv. p. 307; or *Phil. Mag.*, 1896, vol. 42, ser. v. p. 407.

The operations taking place may be stated generally in the following manner. If a condenser in series with an inductance of low resistance is placed as a shunt across the arc, the first effect is to rob the arc of some current to charge the condenser. This action, however, does not decrease, but increases slightly the potential difference of the carbons. Hence the condenser continues to be charged. When the charge is complete, the current through the arc is again stationary, and the condenser at once begins to discharge back through the arc. This, however, increases the current and decreases the potential of the carbons, hence the action proceeds until the condenser is discharged. The process then repeats itself regularly. The whole action is exactly analogous to that by which the resonance of the column of air in an organ pipe controls the operation of the jet of air issuing from the mouth of the pipe and impinging against the sharp edge of the upper lip, and so maintains the sound as long as the current of air is supplied. Mr. Duddell found that the direct current arc between *cored* carbons would not produce this effect. Also he found that in the case of arcs between metal surfaces the arc was even more readily extinguished by shunting the arc with a condenser than in the case of a solid carbon arc. He also found that there were limits to the production of the oscillatory currents by the carbon arc, but that it worked well as a transformer of continuous current to electric oscillations when the condenser and inductance were so adjusted that the frequency lay between 500 and 10,000.

The physical conditions to be fulfilled for this transformation to take place have also been set out mathematically by M. Janet as follows [39] :—

Let C be the capacity of the condenser, L the inductance, and r the resistance of the coil in series with it placed as a shunt across the arc. Let R be the larger resistance placed in series with the arc, and E the electromotive force of the working battery. Let i be the instantaneous value of the current flowing through R, i_1 that through the arc, and i_2 that through the condenser. Then if an alternating current is set up and established in a permanent state in the condenser circuit it has a certain frequency, n. Let $p = 2\pi n$ as usual.

Experiment shows that the current through the arc is also fluctuating, and consists of a periodic current superimposed on a steady current. Therefore the current coming out of the battery must be of the same nature. Let I_0 be the value of this steady current. Then—

$$i = I_0 + I \sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

where I is the maximum value or amplitude of the periodic part of the current through the resistance R. It is also assumed that the frequency of the current through the condenser is the natural frequency of the condenser and inductive shunt. Therefore $n = \dfrac{1}{2\pi\sqrt{\mathrm{CL}}}$ or $p^2 = \dfrac{1}{\mathrm{CL}}$. This circuit, therefore, acts as if it were non-inductive, since

[39] See P. Janet on "Duddell's Musical Arc," *Comptes Rendus*, 1902, vol. 134, p. 821.

the relation between its inductance capacity and frequency is that under which the inductance annuls the capacity.

The main current thus consists of a continuous part and an alternating part. The current through the arc is of the same type, whereas the current through the condenser shunt circuit is purely alternating. If r is the resistance of the inductive shunt, and i_2 is the current through it, then, corresponding to the frequency $n = \frac{1}{2\pi\sqrt{CL}}$, the potential difference of the ends of the inductive shunt must be equal to ri_2, since then the inductance is annulled by the capacity. Hence this must be equal to the electromotive force represented by the periodic part of the main current, which is numerically equal to $RI \sin pt$. Accordingly we have—

$$i_2 = \frac{R}{r} I \sin pt$$

Again, if v is the difference of potential of the carbons forming the arc at any instant, and E is the constant E.M.F. of the working battery, we have also—

$$v = E - Ri$$

or substituting the expression for i above given, we have—

$$v = E - RI_0 - RI \sin pt \quad . \quad . \quad . \quad . \quad . \quad (28)$$

$$\text{But} \quad i_2 = \frac{R}{r} I \sin pt$$

also the current i_1 through the arc is the sum of the current i through the main resistance and the condenser current i_2. Hence—

$$i_1 = i + i_2$$

$$\text{Therefore} \quad i_1 = I_0 + \frac{R + r}{r} I \sin pt \quad . \quad . \quad . \quad . \quad . \quad (29)$$

Differentiate (28) and (29) with respect to time and take the quotient. We have then—

$$\frac{dv}{dt} = - RIp \cos pt \text{ and } \frac{di_1}{dt} = \frac{R + r}{r} Ip \cos pt$$

$$\text{Hence} \quad \frac{dv}{di_1} = - \frac{Rr}{R + r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

If R is large compared with r, the value of $\frac{dv}{di_1}$ approximates to r.

Hence the condition for the establishment of permanent oscillations in the condenser circuit having a frequency $n = \frac{1}{2\pi\sqrt{CL}}$ is that the sign of $\frac{dv}{di_1}$ must be *negative*, and its value numerically equal to, or greater than, that of the ohmic resistance of the shunt circuit. Janet, therefore, arrives at a conclusion as to the essential conditions for the production of the musical arc which is identical with that reached by Duddell. The same result has been reached by Mr. Duddell in another manner by showing that with the above conditions (viz. $\frac{dv}{di_1}$ negative and equal to or greater than r) the energy wasted as heat

in the inductive circuit is recouped during each half period by the energy given to it. Hence the oscillations are maintained.[40]

The high frequency oscillations so produced can, of course, be transformed up to higher potentials by using a Tesla coil or oscillation transformer and placing the primary circuit in series with a condenser as a shunt across the arc.

We are thus able to cause a source of continuous current, such as a secondary battery or dynamo, to expend part of its energy in creating continuous or maintained electric oscillations of high frequency in a condenser and inductive circuit.

Several Italian physicists, however, disagree with Duddell and Janet as to the statement of the laws governing the frequency of the oscillations. Thus, A. Banti has asserted (*Elettricista*, January 12, 1903, vol. 12, p. 1) that with a condenser of 1 mfd. and an extremely small inductance (merely a connecting wire) a frequency of 120,000 may be obtained.[41] Banti says (*loc. cit.*) that the frequency is not the same when the inductance and capacity are varied inversely as one another. Thus, with an inductance of 0·048 henry and capacity of 1 mfd., the frequency is 13,000. With an inductance 0·012 h. and capacity 4 mfds. it is 8500, whilst with 0·003 h. and 16 mfds. it is 2750, whereas if the frequency of the oscillations was entirely determined by the formula $n = \frac{1}{2\pi\sqrt{\mathrm{CL}}}$, the frequency should have been in all cases the same, since the quantity $\sqrt{\mathrm{CL}}$ is preserved constant.

Duddell, however (see a letter in *The Electrician*, 1903, vol. 51, p. 902), has contended that since the value of $\frac{dv}{di_1}$ for the arc with solid carbons is not negative for frequencies as high as 100,000, oscillations cannot be then created in the shunt circuit, and that the statements made concerning very high frequencies are erroneous. In the same letter Duddell points out that, since the full expression for the frequency of the oscillations in an inductive circuit having capacity and resistance is given by $n = \frac{\sqrt{\frac{1}{\mathrm{CL}} - \frac{\mathrm{R}^2}{4\mathrm{L}^2}}}{2\pi}$, it follows that the frequency will be determined by the current through the arc, since the current is a function of the resistance of the arc. Numerical values are not, however, given in confirmation of this opinion.

The reader may be referred to the following sources for additional information :—

M. La Rosa, *Nuovo Cimento*, Jan. 1904, vol. 7, p. 5, " On Duddell's Currents." See also *Science Abstracts*, 1904, vol. 7, A., p. 456.

The above-named author states that his result shows that the actual condenser current is asymmetric. Its amplitude was determined by a Braun vacuum tube. He concludes that—

(i.) The amplitude of the oscillatory current is independent of the

[40] See *loc. cit.*, " On Rapid Variations in the Current through the Direct Current Arc," Appendix II., *Journal of the Inst. Elec. Eng.*, vol. 30, p. 262.

[41] See also *Science Abstracts*, 1903, vol. 6, A., p. 387.

resistance of the shunt circuit until this reaches 2·5 ohms, when the oscillations cease.

(ii.) The change in amplitude with inductance does not follow any simple law.

(iii.) When the main current is small, the amplitude of the shunt current tends to vary inversely as the square root of the inductance, and inversely as the cube root of the capacity.

Corbino has studied the singing arc by stroboscopic methods.

See *Atti. dell'. Assoc. Elettr. Ital.*, 1903, vol. 7, p. 369, also p. 597; or *Science Abstracts*, 1904, vol. 7, A., p. 537.

He says the current in the shunt circuit is not sinusoidal, and that this may be proved by using a Braun cathode ray vacuum tube. Hence, the formula $\frac{1}{2\pi\sqrt{CL}}$ is not strictly applicable for determining the frequency. Corbino deduces an equation for the shunt current i_2 in terms of the constants and the main current i as follows:—

$$L\frac{di_2}{dt} + \left(r - \frac{b}{(i - i_2)^2}\right)\frac{di_2}{dt} + \frac{1}{C} = 0$$

A very full examination of this subject has been made by Maisel (*Physikalische Zeitschrift*, Sept. 1, 1904).[42] He contends that it has been shown by Wertheim Salomonson that a singing arc may produce oscillations having a frequency as high as 400,000, and that the latter observer has photographically registered a frequency as high as 135,000. Also Maisel says that Corbino has shown that the current in the condenser circuit is not sinusoidal, and not even symmetrical, and that the work of Salomonson, Ascoli, and Manzelti has shown that the frequency of the oscillations in the condenser circuit cannot be calculated by the simple formula $n = \frac{1}{2\pi\sqrt{CL}}$.

Maisel bases his views upon the theory of the electric arc developed by Mitkiewiez (see *Russian Journal of Physics and Chemistry*, 1903, pp. 507 and 675) and by J. Stark (*Ann. der Physik.*, 1903, vol. 12, p. 673). According to this theory (which, however, was originally suggested by the author of this book in 1899), the phenomena in the arc very much depend upon the thermal condition of the negative pole.[43] The discharge cannot pass if the temperature of the negative pole falls below a certain limit. If, then, we connect a condenser and inductance as a shunt across the arc, the first effect is to rob the arc of current. This causes a fall of temperature in the electrodes, and finally an extinction of the arc. If, however, the temperature of the negative terminal has not fallen below a certain point, the arc

[42] See also *L'Éclairage Électricque*, 1904, vol. 41, p. 186, for a French epitome of Maisel's paper.

In *The Electrician*, vol. 51, p. 752, will be found a letter from I. Wertheim Salomonson referring to his paper in the *Proceedings of the Royal Academy of Amsterdam* on the effect of variation of current strength on the pitch of the note of the singing arc.

[43] See J. A. Fleming, *Proc. Roy. Soc. Lond.*, 1890, vol. 47, p. 118, "On Electric Discharge between Electrodes at Different Temperatures in Air and High Vacua"; also *Proc. Roy. Institution of Gt. Britain*, 1890, vol. xiii. p. 34, "Problems in the Physics of an Electric Lamp."

relights itself again as soon as the condenser is charged, and the condenser discharges through it. Maisel contends that stroboscopic observations have shown that this extinction of the arc takes place. He states that he has also produced the phenomenon of the singing arc with iron terminals and with mercury and carbon, as well as mercury and iron, and he gives diagrams of current curves taken with a Braun tube which show that the current variation is not sinoidal.

He contends that the sign of the slope of potential in the arc has no importance, and that the singing arc can be obtained with any electrodes and any frequency, and that this frequency cannot be calculated simply from the inductance and capacity in the shunt circuit. On the other hand, all Maisel's observations were made with a shunt circuit, having a capacity of 3·4 mfds. and an inductance of $3 \cdot 4 \times 10^6$ cms. Hence the natural time period of the oscillating circuit was 0·0007 second, which is a frequency less than the value 10,000 given by Duddell as critical.

In a subsequent paper (*Physikalische Zeitschrift*, Jan. 15, 1905) S. Maisel attempts a general theory of the production of undamped trains of electrical oscillations. He assumes the possession of a conductor which rigidly obeys Ohm's law, but has the property that no current flows through it when the electromotive force falls below a certain value, and that the restoration of the current requires a high electromotive force. There are many forms of conductor which comply with these conditions, *e.g.* a vacuum tube, the mercury vapour lamp, as well as the electric arc. The author works out a complete mathematical theory, and shows that when such a conductor is a shunt to a condenser in series with an inductance, a battery or source of steady E.M.F. will create oscillations in the condenser circuit.

These different opinions are to some extent reconcilable when we consider the nature of the *characteristic curve* of a direct current arc. The above term is applied to a curve showing the relation between the current flowing through or out of any electrical appliance whether resistance, motor, lamp, dynamo, or anything else, and the terminal potential difference. Thus the characteristic curve of a resistance is a straight line, thus expressing graphically Ohm's law. The characteristic curve of a series-wound dynamo is a curve resembling the magnetization curve (B, H, curve) of iron. On the other hand, the characteristic curve of a direct current arc is a curve which, if plotted with current as abscissa and potential difference of electrodes as ordinates, is a convex downward sloping curve, as in Fig. 75. If the currents are slowly increased and the points on the curve represent the ratio of arc current to potential difference of the electrodes, the curve is called the *static characteristic;* but if the current runs rapidly through a repeated cycle of values as in the case of an alternating current, then the term of *dynamic characteristic* has been given by Professor H. Th. Simon to the closed curve representing the relation of current and potential differences.

In the case of the direct current (D.C.) arc formed with solid carbons, the static characteristics for various arc lengths are curves similar to those depicted in Fig. 75. It will be noticed that the slope of the curve or the value of $\frac{dv}{di}$ is always negative, and that the

value of $\frac{dv}{di}$, where i denotes the arc current at any instant and v the corresponding potential difference of the carbons, decreases as i increases. Hence $\frac{d^2v}{di^2}$ is positive because $\frac{dv}{di}$ changes from a somewhat large negative value to nearly zero.

It has, however, been shown by Mrs. Ayrton,[44] and by Professor H. Th. Simon,[45] that in the case of an alternating current arc the P.D. of the carbons corresponding to a given current is lower when the current is decreasing than when it is increasing. Hence, if we carry the current through the arc round a cycle of operations,

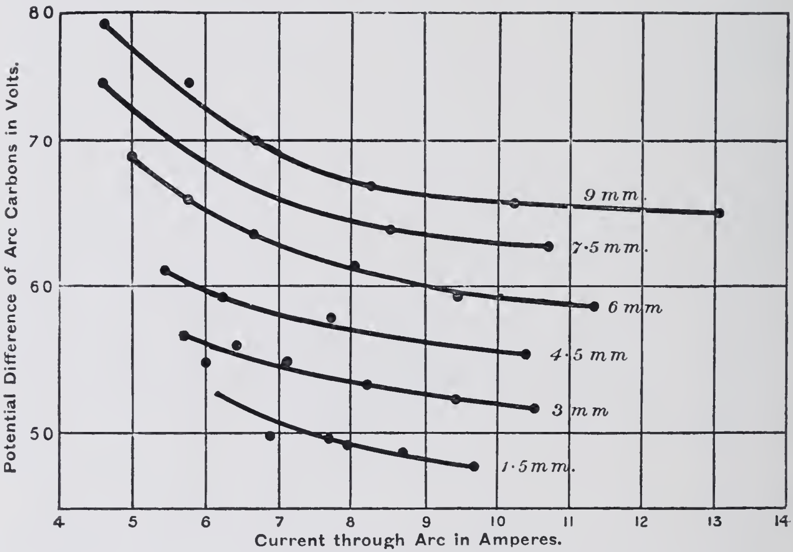


FIG. 75.—Static Characteristic Curves of a D.C. Arc between Carbon Electrodes in Air.

increasing and decreasing, the corresponding *dynamic* characteristic is a closed loop. Simon has shown that the product of area (A) and absolute temperature (T) of the crater of the arc determines the carbon P.D. necessary to produce a given current.[46] Taking this product AT as corresponding to a definite resistance of the arc, he showed that when heat is added from some outside source the characteristic is lowered or a smaller P.D. is required to produce a given current.

If then a continuous current arc is shunted by a condenser in series with an inductive circuit the following is a general description of the actions set up. Assume the condenser charged to the P.D. of

[44] "The Electric Arc," Mrs. H. Ayrton.

[45] *Physical Zeitschrift*, vi. p. 297, 1905. Also *Science Abstracts*, vol. 8A, 1905, *Abs.* 1465, "The Dynamics and Hysteresis of the Electric Arc."

[46] "The Theory of the Singing Arc," H. T. Simon, *Physical Zeitschrift*, vol. 7, p. 423, 1906, or *Science Abstracts*, vol 9A, 1906, *abs.* 1423.

the carbons, and that it is connected across the arc. The condenser begins to discharge. This increases the current through the arc and lowers the carbon P.D. in virtue of the negative slope of the characteristic curve. This, however, facilitates the discharge of the condenser. In virtue of the inductance of the condenser circuit this process continues, and the condenser is not only discharged, but charged up in the reverse direction. The current through the arc then begins to diminish, and this increases the P.D. of the carbons and facilitates the further charging of the condenser. The process is exactly analogous to that by which the steady jet of air from the mouth of an organ pipe sets up steady oscillations of air in the pipe, and these control the motion of the jet of air so as to cause it to play within or without the lip of the pipe, thus maintaining the oscillations. Returning then to the electric phenomenon, we note that since the static characteristic of the carbon arc in air is a curve, with greater slope downwards for small currents than for large, it follows that in the case of a large current arc (10 amperes and upwards) even large variations of the current will produce only small variations of P.D. between the carbons, but with small arc currents (1 or two amperes or less) then even small variations of the current will produce much larger variations in the P.D. of the carbons. If a condenser is shunted across a continuous current arc, and if oscillations are set up in the condenser circuit, we may regard the actual current through the arc as the sum of a constant unidirectional current I_0 and a periodic current, which under assumption of a sine variation may be represented by $I \sin pt$.

The P.D. of the carbons is therefore a function of $I_0 + I \sin pt$, and may be represented by $F(I_0 + I \sin pt)$. This P.D. may in turn be regarded as composed of a constant unidirectional part V_0 and a periodic part $V \sin(pt + \theta)$ differing in phase from the periodic part of the current. The amplitude V of the periodic part of the P.D. will depend upon the part of the characteristic curve at which we are working. If we are on the flat part of the curve characteristic, then variations of current through the arc will only be accompanied by small variations of arc P.D., and this implies also small power given to the condenser circuit.

If then we shunt an arc by a condenser, and gradually reduce the steady current through the arc, the variations of arc current produced by the condenser currents are accompanied by such large variations of arc P.D. that we can employ a small capacity and yet obtain oscillations of considerable current amplitude in the condenser circuit. If, however, we employ a larger arc current, then the variations of potential are small, and we can only obtain sensible oscillations of current by the use of a condenser of relatively large capacity. The matter is not capable of being subjected to strict analytical treatment until we know the form of the function which connects the current and P.D. of the arc, but it is clear that for a given condenser the current in the condenser circuit will be increased by increasing the potential difference variation of the arc electrodes, and this is effected by working with small arc currents on a steep part of the characteristic curve. It is this, perhaps, which accounts for the difference of opinion between various observers as to the possible limits of

frequency obtainable by the original Duddell method of shunting an ordinary carbon arc with a condenser. Those observers who used, say, a 10-ampere arc and a condenser having a capacity of 1 mfd. or so obtained only relatively low frequency oscillations, and could not obtain very high frequency because by using a condenser of small capacity the variations of arc current were too small to convey sensible energy to the condenser circuit. Those, however, who employed a small capacity and small arc current were enabled to obtain oscillations of much higher frequency.

In 1903, however, V. Poulsen made known the interesting discovery, viz. that by employing a continuous current arc formed with carbon and cooled metal electrodes in an atmosphere of hydrogen or coal gas or any hydrocarbon, it was possible to obtain in an inductive

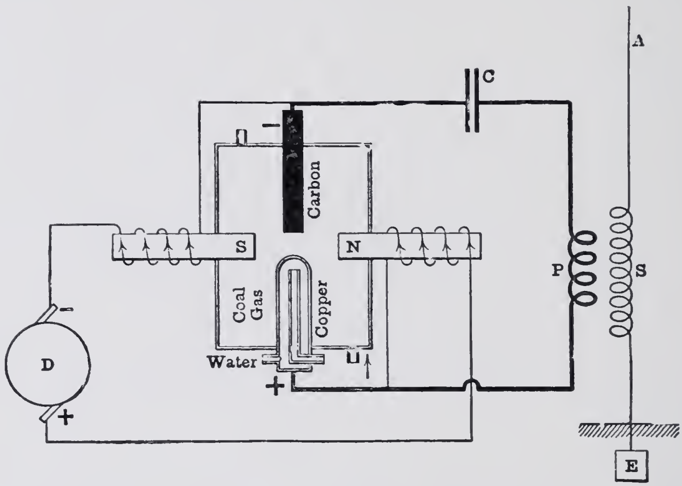


FIG. 76.—Poulsen's Arrangement for producing Undamped Electric Oscillations.

shunt circuit having a small capacity very high frequency vigorous oscillations, practically undamped.[47] He showed that when the oscillatory arc was placed in a magnetic field transverse to the arc the condenser plate potential difference was very greatly increased. He found that if the continuous current arc was formed inside a flame such as that of a spirit lamp it was possible to obtain oscillations of much higher frequency, by appropriately shunting the arc with a small capacity and large inductance, than with the ordinary Duddell musical arc. Hence Poulsen adopted the following arrangement. An electric arc is formed between the end of a thick carbon rod kept in slow rotation and a water-cooled copper rod, the latter forming the anode or positive pole of the arc (see Figs. 76, 77). This

[47] See V. Poulsen, British Patent Specification, No. 15,599, of 1903; also *Transactions of the International Congress of Electricians at St. Louis*, vol. 2, p. 963, 1905; or *Science Abstract*, vol. 8A; *Abs.* 1620, 1905; also *The Electrician*, vol. 58, p. 166, November 16, 1906. A report of a Lecture given by Mr. V. Poulsen in the Queen's Hall, London.

arc is created in a box kept full of coal gas or vapour of hydrocarbon, with a continuous voltage of 400 to 500 volts. A variable resistance is placed in series with the arc and choking coils in both leads. The arc box is also perforated by two magnetic poles which produce a powerful field at right angles to the arc. The arc electrodes are connected outside the box by a condenser circuit consisting of a small capacity and a large inductance. The capacity may be something of the order of 0·004 of a microfarad and the inductance of the order of 100,000 cms. or 0·1 of a millihenry. Under these circumstances, when the arc is started, powerful oscillations, which are practically continuous

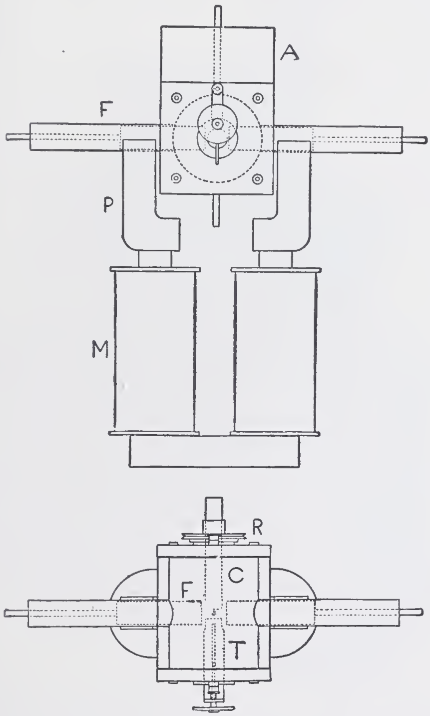


FIG. 77.—Poulsen's Arrangement for producing Undamped Electric Oscillations.

or undamped, will be set up in the condenser circuit. Attention to several details is necessary to secure the best results. The carbon rod must have a square, sharp edge, and the arc must spring from this edge to a copper nose on the end of the cold copper electrode. The carbon must be kept in very slow, steady rotation. The magnetic field must be very strong, and the arc must have a certain length, best found by trial. The arc box must be kept cool, and also the copper electrode, by circulating water. In the case of portable apparatus Poulsen uses air cooling, the arc being contained in a box with metal flanges and the hydrocarbon vapour being formed by dropping alcohol or petrol into the box (see Fig. 78).

It has been shown by the author that even then the oscillations

are not quite continuous.[48] The oscillating arc tends to break up into a series of intermittent discharges, and it is somewhat difficult to obtain absolutely unbroken undamped oscillations. Some interesting investigations were carried out in the author's laboratory in 1907 by Mr. W. L. Upson, on the characteristic curves of electric arcs between various electrodes and in different gases.[49] These experi-

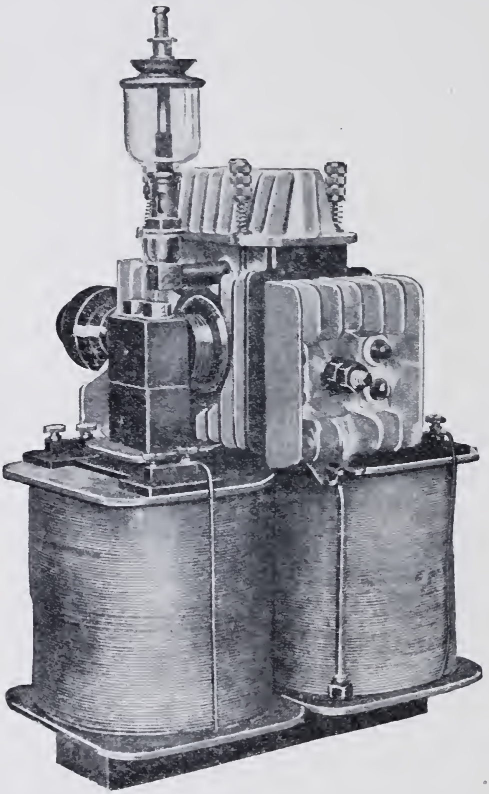


FIG. 78.—Poulsen's Arc Apparatus for producing Undamped Electric Oscillations.

ments showed that for an arc taken between a carbon (negative) and a water-cooled copper (positive) electrode the characteristic curve is much steeper at and about the same arc current, than for the carbon-carbon arc in air (see Fig. 79). Hence it is clear that one element in Poulsen's discovery is the effect of hydrogen or hydrocarbon

[48] See J. A. Fleming, "On the Poulsen Arc as a Means of generating Undamped Oscillations," *Phil. Mag.*, August, 1907; also *Proc. Phys. Soc., Lond.*, vol. 20, 1907; also "Recent Advances in Electric Wave Telegraphy," a discourse at the Royal Institution. See *The Electrician*, May 31, June 7, 14, 21, 1907.

[49] See W. L. Upson, "Observations on the Electric Arc," *Proc. Phys. Soc., Lond.*, vol. 20, 1907, or *Phil. Mag.*, July, 1907. Also J. A. Fleming, "Some Observations on the Poulsen Arc as a Means of obtaining Continuous Electric Oscillations," *Phil. Mag.*, August, 1907, series vi. vol. 14, p. 254.

vapour in steepening the characteristic curve of the direct current arc. The reason for this has not yet been fully explained.

Poulsen immediately applied the above method for producing undamped electric oscillations in radiotelegraphy, with the co-operation of P. O. Pedersen.[50]

We shall return again, in Chap. X. on radiotelegraphic stations, to the consideration of the practical use of Poulsen's discovery and apparatus in wireless telegraphy and telephony.

Meanwhile the reader's attention may be drawn to one or two other points in connection with the production of electric oscillations by the arc.

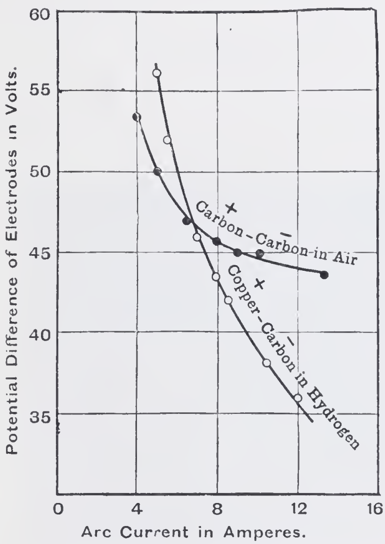


Fig. 79.—Diagram showing Results of Upson's Experiments on Characteristic Curves of Arcs.

Much light has been thrown on the nature of the phenomenon by the careful researches of Professor H. Th. Simon.[51] He has studied, by means of the oscillograph and Braun vacuum tube, the form of the current curves in the two circuits: the main or arc circuit and the shunt or oscillatory circuits. He shows that the arc current consists of a sinoidal current superimposed upon a steady current, and that the current in the shunt circuit is nearly a sinoidal current. It follows from this that the arc current increases and decreases periodically. Since the main current keeps constant, it follows that the current through the arc is increasing when that into the condenser is decreasing, and *vice versâ*.

The form of the oscillograms and characteristic curve of the arc when the current is periodic is well shown by some oscillograms and characteristic curves taken by Professor J. T. Morris with alternating current arcs under various conditions in air and in coal gas.[52]

Thus in Figs. 80 and 81 are shown the oscillograms of an alternating current arc in air, formed with 440 and 110 volts respectively, at a frequency of 60. In the case of Fig. 80 the wave of current has been shifted through 180° to keep well separate the curves of voltage

[50] See V. Poulsen, "A Method for producing Undamped Electric Oscillations and its Employment in Wireless Telegraphy," *The Electrician*, vol. 58, p. 166, 1906. In this article a number of diagrams are given showing the type of receiving circuit used.

[51] See H. T. Simon, "The Dynamics and Hysteresis of the Electric Arc," *Phys. Zeitschrift*, vol. 6, p. 297, 1905, or *Science Abstracts*, vol. 8A, *abs.* 1465; also "Theory of the Singing Arc," *Phys. Zeitschrift*, vol. 7, p. 433, 1906, or *Science Abstracts*, vol. 9A, *abs.* 1423.

[52] See J. T. Morris, "Note on an Oscillographic Study of Low Frequency Oscillating Arcs," *Electrical Review*, August 9, 1907. A paper read before the British Association at Leicester, 1907.

and current. It will be noticed that the current remains practically constant for quite a sensible time during the semi-period, and that during that time the P.D. of the carbons rises rapidly, but falls again quickly. The P.D. then remains nearly zero for some time as the current reverses sign. These values of P.D. (in volts) and current (in amperes) are set off in cyclical curves in Figs. 82 and 83, which show well the cycle of changes of current and P.D. in an alternating current arc, and the difference between the arc in air and in coal gas, both with and without a transverse magnetic field across the arc. The effect of the coal gas is seen in the much more sudden and greater rise of the curve as the current passes through zero, and also in the much steeper, falling characteristic as the current increases to its maximum.

The reasons, then, for the peculiar form of the closed characteristic curve for an alternating current arc are to be found in the

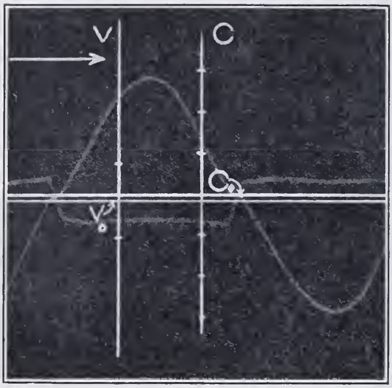


Fig. 80.—Oscillograms of 440-volt Alternating Arc in Air. The Current Curve is the square shouldered curve, and is reversed or shifted through 180°. (J. T. Morris.)

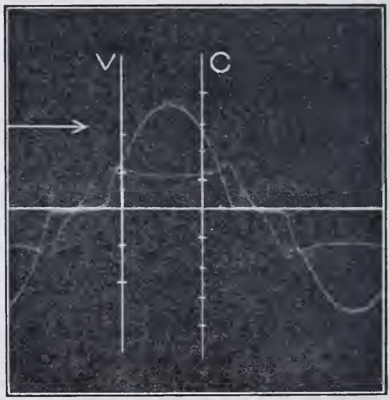


Fig. 81.—Oscillogram of 110-volt Alternating Arc in Air. The Current Curve is the square shouldered Curve. (J. T. Morris.)

phenomena of the arc and of gaseous conductors generally. If we apply a steady potential difference to two arc electrodes immersed in a gas, there is a great resistance to the passage of electricity, which chiefly resides at the negative electrode, and can be enormously reduced by heating that electrode.

Again, a gaseous conductor does not obey Ohm's law. Its conductivity is not constant, but is a function of the voltage, and in general there is a constant value, called the saturation current, which the current cannot exceed no matter what the voltage. If we consider the instant when the current through the arc is zero, the conductivity of the arc or interelectrode vapour is then very small, and the electrode P.D. therefore rises to its full value. If, however, any of the gas is ionized by any cause, then these ions are moved by the electric force and a current begins to flow. As the current increases the conductivity of the gas increases, and the electrode or arc

P.D. falls. When the arc current has reached its maximum value and commences to decrease, the electrodes still remain hot and the interelectrode conductivity remains good; therefore the arc P.D. keeps low until the current is nearly zero again, when the cooling of the electrodes causes a slight rise in current to be followed by a fall to zero, and then reversal and rapid increase in the negative direction. The useful effect of the coal gas or hydrogen is largely due to its cooling effect, for as soon as the arc current falls to zero the hydrogen or coal gas cools the electrodes and so promotes a rapid increase in arc resistance and therefore a quick and large rise in P.D. between the

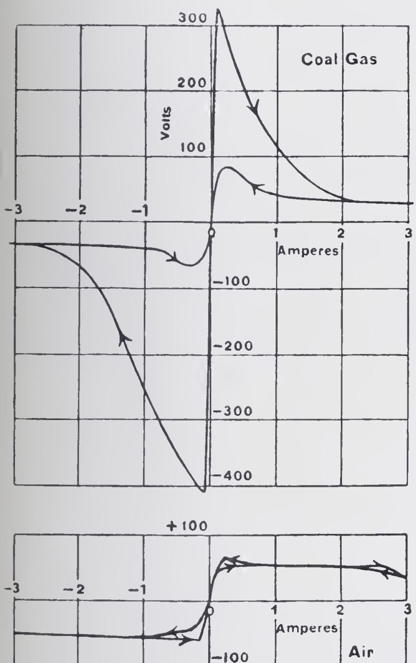


FIG. 82.—Cyclical or Dynamic Characteristic Curve of a 440-volt Arc in Coal Gas (Upper Curve) and Air (Lower Curve) without Transverse Magnetic Field. (J. T. Morris.)

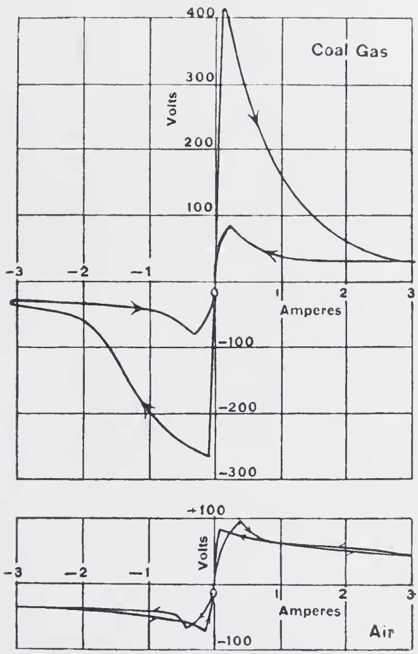


FIG. 83.—Cyclical or Dynamic Characteristic Curve of a 440-volt Arc in Coal Gas (Upper Curve) and Air (Lower Curve) with Transverse Magnetic Field. (J. T. Morris.)

electrodes. The transverse magnetic field helps to extinguish the arc more quickly. We thus find an explanation of the peculiar form of the cyclical characteristic curve. These cyclical or dynamic characteristics of the alternating current arc have been compared by H. Th. Simon with the magnetic hysteresis loops of iron and the static characteristics with the ordinary non-cyclical magnetization curve.

If a condenser is shunted across the arc it is then clear that oscillations once started will tend to persist. For the initial connection of the condenser robs the arc of some current, and this

reduction of current at once increases the electrode or arc P.D. which is in the direction required to continue the charging. When the condenser is fully charged the arc current becomes again constant or rises to its steady value. This is accompanied by a fall in arc P.D., and the condenser then discharges through the arc, thus increasing the arc current still more and further decreasing the arc P.D. The changes in arc P.D. are then always automatically made in the direction necessary to give and take energy from the condenser periodically, and the process is self-sustaining. The process is greatly facilitated by immersing the arc in an atmosphere which does not act chemically on the electrodes and at the same time cools them. It is therefore assisted by surrounding the electrodes with an atmosphere of hydrogen or hydrocarbon, and also helped by replacing the negative carbon by a water-cooled copper cathode. It is also aided by a magnetic field placed transversely to the arc, because this tends to rupture the arc very suddenly and hence brings into play the inductances of the condenser and main circuit to increase the electromotive force in the circuit which charges the condenser. Hence it follows that the root-mean square value of the P.D. of the terminals of the condenser as measured by an electrostatic voltmeter may be many times greater than the P.D. of the arc electrodes as measured by a direct current voltmeter. If V_0 is this last voltage and V_1 is the R.M.S. value of the true periodic or alternating P.D. at the terminals of the condenser, which may be for the moment assumed to have a sinoidal form and frequency $n = \frac{p}{2\pi}$, then the reading V of an electrostatic voltmeter placed across the terminals of the condenser would be—

$$\sqrt{\frac{1}{T}\int_0^T (V_0 + V_1 \sin pt)^2\, dt} = \sqrt{V_0^2 + V_1^2}$$

Hence $\qquad V^2 = V_0^2 + V_1^2, \quad$ and $\quad V_1 = \sqrt{V^2 - V_0^2}$

Thus, if $V_0 = 400$ volts, V may be as much as 1600 volts.

It is found by experience that in using the carbon-copper arc in coal gas to produce vigorous undamped oscillations, the capacity in the shunt circuit should be small and the inductance large. Thus, when using an 8-ampere arc formed with 400 volts the capacity can conveniently be about 0·005 mfd., or 4000 to 5000 cms. in electrostatic measure, and the inductance about 20 times as great, viz. 100,000 cms. in electromagnetic measure.

The general conditions which have to be complied with to obtain by this method powerful oscillations of a frequency high enough to be of use in radiotelegraphy, viz. of the order of 10^6, are as follows :—

The numerical value of the capacity C_{ES} when reckoned in electrostatic units must be small compared with the numerical value of the inductance L_{EM} reckoned in electromagnetic units, and the capacity and inductance must have such values that the quantity $\frac{3 \times 10^{10}}{2\pi\sqrt{C_{ES} \times L_{EM}}}$ which measures the frequency must be of the order of 10^6.

The arc used should be a high potential small current arc and

used under such conditions that it is worked at a steep part of the characteristic curve. It is therefore essential to work the arc in a non-oxygenic atmosphere, and experience shows that the best results are obtained with a hard carbon anode and cooled copper anode in an atmosphere of hydrocarbon gas.

Amongst other investigations on this subject those of L. W. Austin [53] may be mentioned. He experimented with electric arcs formed between various materials, such as solid carbon, cored carbon, graphite and metals, and found that high frequency oscillations could be produced with graphite electrodes, the frequency being of the order of 100,000 and upwards, when the arc was formed in air. He found, as Poulsen and others had previously done, that vigorous high frequency oscillations can more easily be formed by an arc with copper-carbon electrodes placed in a gas flame or in an atmosphere of hydrogen; the arc in hydrogen or coal gas enabling very large quantities of energy to be given up to the oscillating circuit without extinguishing the arc. Austin also found he could produce similar effects with the arc formed in steam and in compressed air.

A point of importance in connection with this subject is whether the oscillations produced in the shunt circuit are controlled as to frequency solely by the inductance and capacity of that circuit—in other words, whether the oscillations are free or forced.

It appears from Austin's experiments that there is always a fundamental oscillation, the frequency n of which is not far from that given by Thomson's law, viz. $n = \frac{1}{2\pi\sqrt{CL}}$; but that there are higher harmonics as well, and also that the fundamental frequency is to some extent a function of the arc length and arc currents. Also he agrees with the author that for high frequencies there is a tendency for the oscillations to become discontinuous and break up into separate trains of oscillations.

15. The Production of rapidly repeated Trains of Damped Oscillations.—In the ordinary use of the induction coil operated with a hammer or mercury break the number of interruptions of the primary circuit may be about 50 per second, and when an alternating current is substituted for the induction coil the number of alternations will usually be about 50 to 100 per second. If we suppose that a condenser is charged by such a coil or transformer, and that 50 damped trains of oscillations are thus created per second, and that each train contains 20 complete oscillations, and that the oscillation frequency is 10^6, we see at once that the time during which oscillations are actually taking place is only one-thousandth part of the whole time during which the process continues. It is obvious therefore that much may be done by closing up the intervals between the trains of oscillations, so as to occupy more of the whole time with oscillations. There are several methods by which this can be done.

The first of these is by the use of a short spark gap and induction coil. If a coil has its secondary terminals connected by a condenser

[53] L. W. Austin, "On the Production of High Frequency Oscillations from the Electric Arc," *Bulletin of the U.S.A. Bureau of Standards*, vol. 3, No. 2, Washington, 1907.

of no very large capacity, say, by a Leyden jar of 0·004 mfd. capacity, and the spark gap across the secondary is made short, say, 1 mm., then several discharges of the jar take place at each interruption of the primary circuit of the coil. This can be proved by the aid of the author's spark counter described in § 15, Chap. II. The explanation is that as the electromotive force rises up in the secondary circuit of the coil, when it reaches the value corresponding to the length of the short gap it causes a discharge, but since the electromotive force continues to exist it again repeats the charging, and hence 3, 4, or 5 or more sparks may occur at each interruption of the primary. It must, therefore, not be assumed that when we have 50 interruptions of the primary circuit per second we have the same number of secondary sparks, there may be many more. The same thing happens in the case of the alternate current transformer. There may be many more sparks than alternations of the primary current. It is, however, necessary to insert in the primary circuit of the transformer a large inductance which serves to arrest the current which would otherwise start an arc across the balls immediately the spark takes place. By the use of a suitable inductance in series with the primary of a coil actuated from a public electric supply of alternating current having a frequency of 40, Professor Q. Majorana, in 1904, succeeded in obtaining a series of 10,000 short sparks per second for the purposes of wireless telephony.[54] This phenomenon of multiple sparks per interruption had previously been noticed by H. Abraham (see *Bulletin Soc. Franc. de Phys.*, May 5, 1899) and by A. Blondel (see British Patent Specification, No. 21,909 of Dec. 3, 1899), but had not previously been utilized. Majorana states that blowing air or carbonic acid on the spark gap serves to keep down the temperature of the balls and maintain a steady state.

Such a multiple spark examined in a revolving mirror presents itself as an unbroken band of light, unless the speed of the mirror is very large.

A very similar multiplication of discharges can take place when a mercury lamp or bulb full of mercury vapour is substituted for a spark gap.

Mr. P. Cooper-Hewitt, in investigations connected with the production of a mercury-vapour incandescent lamp, found that a column of mercury vapour has electrical properties very similar to that of the electric arc between solid carbons. If a glass tube is provided with mercury electrodes connected by sealed-in platinum wires with a circuit, and if the tube is highly exhausted of air so as to contain only mercury vapour, it is found that this vapour becomes electrically conductive when a continuous voltage is supplied to the ends of the tube which exceeds a certain limit.[55]

The tube when cold offers a high resistance, and this appears to reside chiefly at the negative mercury electrode. If, however, a high

[54] See *The Electrician*, vol. 53, p. 991, 1904, October 7; also *Elektrotechnische Zeitschrift*, vol. 25, p. 943, 1904.

[55] A general description of the phenomena connected with the arc discharge in mercury vapour has been given by Mr. H. P. Wills, in a paper on the "Conduction of Electricity in Mercury Vapour," in the *Physical Review* for August, 1904, vol. xix. p. 65; see also a paper by P. C. Hewitt, *Electrical World and Engineer* of New York, April 27, 1901, p. 679.

voltage is momentarily applied, the resistance falls, and a moderate voltage of 50 or 100 volts will then maintain a current of several amperes through the tube, provided the tube has a sufficient diameter. When a certain current passes, the mercury vapour glows brilliantly with a bright greenish light. The efficiency of the device as a source of light is high. A tube taking 3 amperes at 60 volts will emit a light of 180 candles, and has therefore an efficiency of 0·5 watt per candle.

If a mercury vapour lamp has its terminals shunted by a condenser in series with an inductive resistance, and a high voltage is applied to the terminals of the tube, the result is to excite electrical oscillations in the condenser circuit, including the condenser, inductance, and tube. Assuming the voltage to be alternating, the operations are as follows:—

As the voltage rises from zero the condenser becomes charged, but the mercury vapour tube does not conduct. At a certain critical voltage the resistance of the mercury vapour suddenly disappears or falls greatly, and a current passes through it. The condenser then discharges through this low resistance with oscillations, and when the voltage again falls below a certain value, the mercury vapour ceases to be a good conductor, and remains of high resistance until the voltage rises again and the process repeats itself. Owing to this high initial resistance, it requires about 5000 volts alternating to maintain a current of 2 amperes through a tube which will take the same current at 100 volts continuous.[56] Based on these facts, Mr. Cooper-Hewitt has devised a mercury vapour current interrupter, as follows:—

A large glass bulb about 8 or 10 inches in diameter has a pair of tubular extensions with platinum wires sealed in at the bottom. These tubes are partly filled with mercury (see Fig. 84). The globe is exhausted of air, and contains only mercury vapour. It may be put in a vessel of oil to keep it cool.

The platinum terminals are connected to a high voltage low frequency circuit, such as the secondary terminals of a 20,000-volt transformer, and the terminals are also shunted by a condenser and an inductance, which may be the primary circuit of an oscillation or high frequency induction coil. When the low frequency voltage is turned on, the mercury vapour between the electrodes is a nonconductor until the voltage reaches a certain high value, say 10,000 or 15,000 volts. The bulb then suddenly becomes a good conductor due to the disappearance of the cathode resistance. Then the condenser discharges with oscillations and the voltage drops. At a certain low voltage, which can be adjusted, the cathode resistance again reappears and the bulb ceases to conduct. Hence it acts like a spark gap, but with much greater regularity. The behaviour of the interrupter as a substitute for a spark gap in producing the oscillatory discharge of a condenser has been investigated by Professor G. W. Pierce, of Harvard University. He employed one of the double-pool mercury

[56] See *Science Abstracts*, 1904, vol. 7, A., p. 347; also British Patent Specification, P. Cooper-Hewitt, No. 9206 of 1903; also *Electrical World* of New York, Feb. 21, 1903, vol. 41, p. 316, and *Electrical Review* of New York, Feb. 21, 1903, vol. 42, p. 264.

type of Cooper-Hewitt bulbs, and considered its application especially to wireless telegraphy.[57] He operated with alternating currents, and found that several discharges may occur within a single half period of the transformer current. Thus with 15,000 volts, and a capacity of 0·117 mfd., one or two discharges per half period were obtained.

With a small capacity of about 0·001 mfd. and the same voltage over 200 discharges per half period, that is, in $\frac{1}{120}$ of a second, were

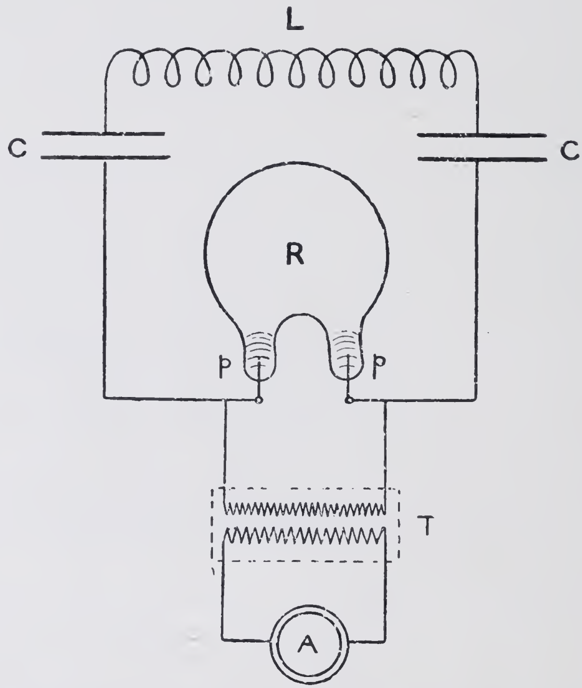


FIG. 84.—Mode of employing the Cooper-Hewitt Mercury Vapour Current Interrupter in place of a Spark Gap. R, vacuous glass bulb containing mercury vapour; *p*, *p*, mercury electrodes; A, alternator; T, transformer; C, C, condensers; L, inductance.

produced. The complete discharges were separated only by $\frac{1}{100000}$ of a second.

The discharges of this particular interrupter always began at 7070 volts, and the condenser was left charged at about 1600 volts, sometimes positive and sometimes negative.

It was found that the resistance of the interrupter decreased with increasing capacity (C) and decreasing inductance (L) in the oscillatory circuit, and varied from 0·127 ohm for L = 0·000011 henry and

[57] See G. W. Pierce, "On the Cooper-Hewitt Mercury Interrupter," *Proc. Amer. Acad. of Science*, 1904, vol. 39, No. 18, p. 389. Also *Science Abstracts*, vol. 7, A., p. 346.

C = 0·117 mfd., to 0·598 ohm for L = 0·00142 henry and C = 0·073 mfd.

The mercury interrupter seems to act, therefore, as a very low resistance air gap, but with much greater uniformity. On the other hand, attempts to use it for large powers have not been very successful.

16. Multiple Transformation of Oscillations.—Since electric oscillations are only alternating electric currents of high frequency, they can be transformed as regards voltage and current by means of suitable oscillation transformers. By this means it is possible to multiply the frequency so as to make relatively low frequency trains of oscillations generate trains of higher frequency.

One of the means for so doing was devised by the author in

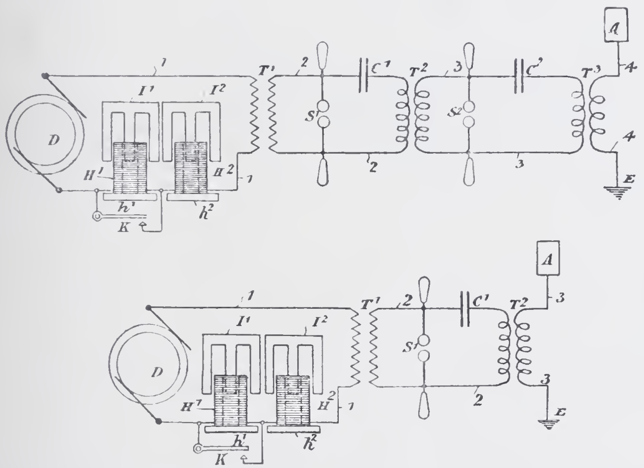


Fig. 85.—Arrangement of Circuits for Multiple Transformation of Oscillations. (Fleming.)

1900,[58] and put into practice on a large scale in the first equipment of the first long-distance Marconi radiotelegraphic station, established at Poldhu, in Cornwall, England, for transatlantic radiotelegraphy. The following is the arrangement:—

A high-tension alternator, D (see Fig. 85), provides an alternating current having a frequency, say, of 50 at a pressure of 2000 volts. This current passes through the thick wire of an ordinary high-tension transformer, T^1, and is transformed up to 20,000 or 30,000 volts. Across the secondary terminals of this transformer are connected a pair of spark balls, S^1, a condenser, C^1, and the primary coil of an oscillation transformer, T^2. The secondary circuit of this last is connected in turn to a second pair of spark balls, S^2, and to a condenser, C^2, and the primary circuit of a second oscillation transformer, T^3. The secondary circuit of this last transformer then provides oscillatory discharges of extra high tension and

[58] See British Patent Specification of J. A. Fleming, No. 3481, of Feb. 18, 1901; also U.S.A. Patent Specification, No. 750,004.

high frequency, and a large number of trains of oscillations per second.

These several circuits having each capacity and inductance are "tuned" to each other, that is to say, have their capacity and inductance so adjusted that taken separately they have the same natural time period of electrical oscillation. Hence they are said to be in resonance. When the alternator is set in action the operation of the apparatus is as follows: At each alternation of the current in the alternator, a current traverses the first transformer T^1, and creates alternations of potential which charge the condenser C^1. If the circuit composed of the secondary circuit of the transformer T^1, the primary circuit of the transformer T^2, and the condenser C^1 has its capacity and inductance adjusted to be in resonance with the low frequency (say 50) of the alternator, then powerful oscillations will accumulate in it, which at intervals will discharge across the spark gap S^1. Thus there will not be 100 sparks per second at S^1, corresponding to the 50 frequency, but perhaps 10 or 12. At each of these sparks the condenser C^1 discharges with oscillations and gives rise to a long train of damped oscillations. These are transformed up in potential by the Transformer T^2, and in like manner charge the condenser C^2, and, if the circuit of this condenser is properly tuned to the circuit of the condenser C^1, then, in like manner, powerful oscillations are set up in the circuit composed of C^2 and T^3, and when sparks occur at the second spark gap S_2 we have high potential high frequency oscillations in the circuit of C^2 which consist of multiple trains of oscillations, a group of trains in the circuit of C^2 corresponding to each one in the circuit of C^1. Special means have to be provided for preventing the arcing at the primary spark balls, which will be described in a later chapter.

We shall show in Chap. III. that when two oscillatory circuits are in tune and coupled together inductively, oscillations of two frequencies are created in them by their mutual reaction. Hence in the above-described arrangement the effect produced in the last oscillation circuit is a very complex one, and cannot be described as a simple series of trains of oscillations of one period. Nevertheless, the double transformation system serves to create trains of high frequency oscillations from other trains of lower frequency, and these again from extremely low frequency transformer discharges.

Another arrangement of circuits employing more than one spark gap and capable of producing two sets of oscillations in any relative difference of phase is one due to L. Mandelstam and N. Papalexi. In this case there are three circuits—I., II., and III. (see Fig. 86). A pair of spark balls, S_1, are connected to a transformer or an induction coil, and are also connected by two circuits having capacity and inductance. Circuit I. has a capacity C_1 and inductance L_1, and circuit III. has capacity C_3 and inductance L_3, and includes also a spark gap S_2 which is short-circuited by a very large inductance L, which does not prevent the charging of the condensers C_3, but acts as a perfect choker to high frequency oscillations. The spark gap S_2 is also closed by the circuit II. having capacity C_2 and inductance L_2. If, then, the induction coil or transformer is set in operation, the condensers C_1 and C_3 are charged, and when the insulation of the

spark gap S_1 breaks down, oscillations are set up in circuit I. such that if we represent the current i_1 at any instant by the expression, then—

$$i_1 = -\frac{V}{pL_1}\epsilon^{-\delta t}\sin pt$$

where V is the spark potential of the gap S_1 and $p = 2\pi$ times the frequency of the oscillations set up, or $p = \frac{1}{\sqrt{C_1L_1}}$. After the expiration of a certain time, t_1, which is determined by the constants of the circuit III., a spark appears at S_2 and oscillations begin in the

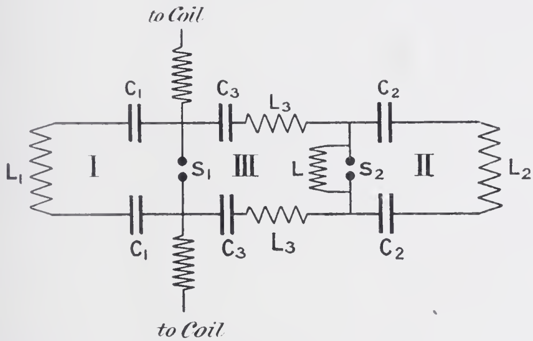


FIG. 86.—Mandelstam and Papalexi Circuit for producing Oscillations with any required Phase Difference.

circuit II. such that the current i_2 at any instant may be represented by the expression—

$$i_2 = -A\epsilon^{-\delta(t-t_1)}\sin\left[p(t-t_1)+\alpha\right]$$

Henceforth the oscillations in I. and II. run on with a constant phase difference, $pt_1 - \alpha$. These constants can be experimentally and theoretically determined. Mandelstam and Papalexi have shown that $\alpha = 180°$ and $t_1 = \frac{\pi}{n}$, and that $A = \frac{2VC_3}{L_2p\,(C_2+C_3)}$. The process provides a means of setting up damped oscillations with definite phase difference. For additional details the original paper must be consulted.[59]

[59] See L. Mandelstam and N. Papalexi, "On a Method of obtaining Oscillations in different Phases," *Phys. Zeitschrift*, vol. 7, p. 303, 1906, or *Science Abstracts*, vol. 9A, 1906, *abs.* 1277.

PLATE I.—DIAGRAMS SHOWING THE OSCILLATORY DISCHARGE OF A CONDENSER FROM PHOTOGRAPHS TAKEN WITH THE DUDDELL OSCILLOGRAPH IN THE PENDER ELECTRICAL LABORATORY, UNIVERSITY COLLEGE, LONDON.

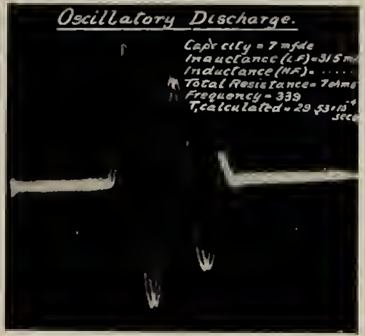


FIG. 1.—Capacity, 7 mfds.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 7 ohms; frequency, 339.

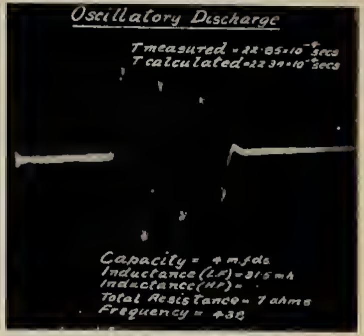


FIG. 2.—Capacity, 4 mfds.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 7 ohms; frequency, 438.

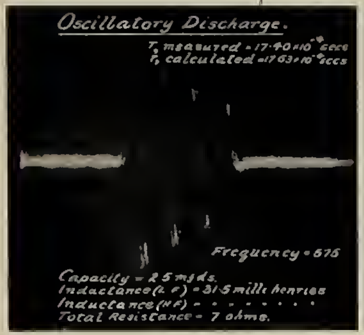


FIG. 3.—Capacity, 2·5 mfds.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 7 ohms; frequency, 575.

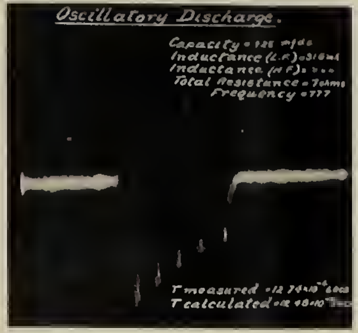


FIG. 4.—Capacity, 1·25 mfds.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 7 ohms; frequency, 777.

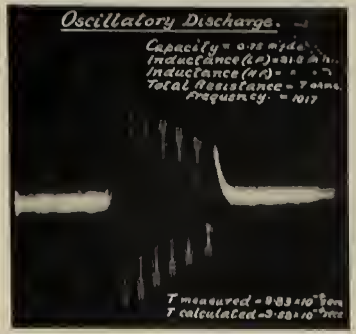


FIG. 5.—Capacity, 0·75 mfd.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 7 ohms; frequency, 1017.

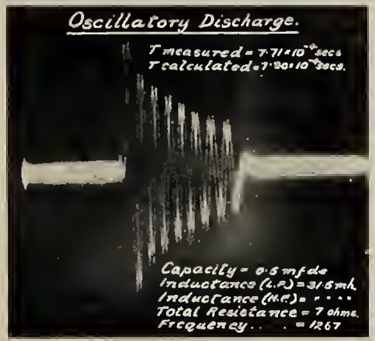


FIG. 6.—Capacity, 0·5 mfd.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 7 ohms; frequency, 1265.

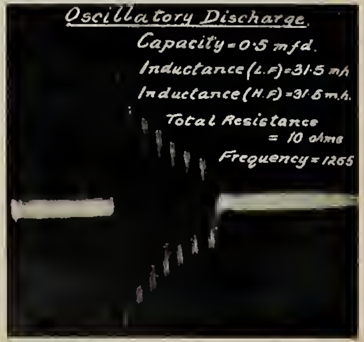


FIG. 7.—Capacity, 0·5 mfd.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 10 ohms; frequency, 1265.

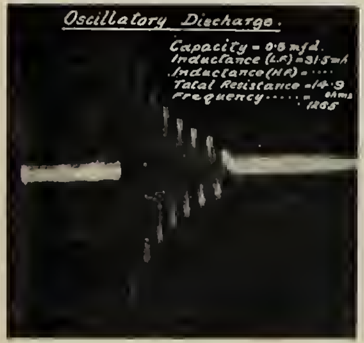


FIG. 8.—Capacity, 0·5 mfd.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 14·9 ohms; frequency, 1265.

FIG. 9.—Capacity, 0·5 mfd.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 23 ohms; frequency, 1265.

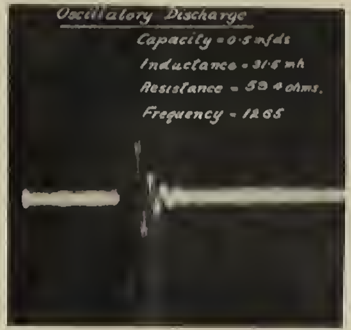


FIG. 10.—Capacity, 0·5 mfd.; inductance, $31{\cdot}5 \times 10^6$ cms.; resistance, 59·4 ohms; frequency, 1265.

[To face p. 110.

CHAPTER II

HIGH FREQUENCY ELECTRIC MEASUREMENTS

1. The Essential Difference between High and Low Frequency Electric Measurements. High Frequency Electric Resistance.—The measurement of high frequency electric currents and potentials and other specific qualities of electric conductors and insulators, when subjected to the action of electric oscillations, to a considerable extent calls for the employment of special instruments and methods. The processes and means used for the measurement of low frequency alternating electric currents and potentials are not always applicable or correct if applied in high frequency measurements. The cardinal reason for the difference between the two cases is to be found in the fact that a high frequency current does not penetrate into the interior of a thick solid metallic conductor of good conductivity, but is a surface effect. Furthermore, inductances and condensers act towards high frequency currents in a manner quite different from that in which they act towards continuous or low frequency currents. A coil of wire of many turns may act as an almost complete barrier to electric oscillations, and, on the other hand, a condenser which, when interposed in a circuit, will either prevent or reduce the flow of a continuous or low frequency current may actually increase the current if inserted in a high frequency circuit.

As we are much concerned when dealing with electric oscillations with the resistance, inductance, and capacity of circuits in which rapidly reversed electromotive forces exist, it is necessary to consider in the first place the manner in which these qualities are affected by the frequency.

Every electric circuit consists of a so-called conductor, immersed in an insulating material or non-conductor. When traversed by an alternating current there are five qualities of the circuit to be considered :—

(i.) The *resistance*, or reciprocally the *conductance* of the conductor.

(ii.) The *inductance* of the conductor, depending on its geometrical form, material, and the nature of the surrounding insulator.

(iii.) The *capacity* of the conductor, depending on its position with regard to the return circuit and other circuits, and on the nature (*dielectric constant*) of the insulator surrounding it.

(iv.) The *dielectric conductance*, or reciprocally the *insulation resistance* of the insulator.

(v.) The *energy dissipating power*, due to causes other than conductance (such as the *dielectric hysteresis*) which exist in the insulator or dielectric.[1]

[1] Under this heading we must also include such sources of energy dissipation as brush discharges through the air over the surface of the dielectric or between conductors.

The resistance of a circuit may be defined as that quality of it in virtue of which energy is dissipated as heat when a current flows through it. The ordinary volume resistivity is the resistance per unit cube, *i.e.* of one centimetre cube under uniform electric current flow between opposed faces.

The resistance under the action of uniform current flow may be called the steady resistance and will be denoted by R.

The power dissipated as heat in a conductor of steady resistance R when a uniform unidirectional current A is flowing through it is measured by A^2R, and the resistance R may therefore be defined as the quotient of the total energy dissipation per second, viz. A^2R, by the square of the current A.

In this case the current is uniformly distributed over the cross-section of the conductor, that is, has uniform current density. If,

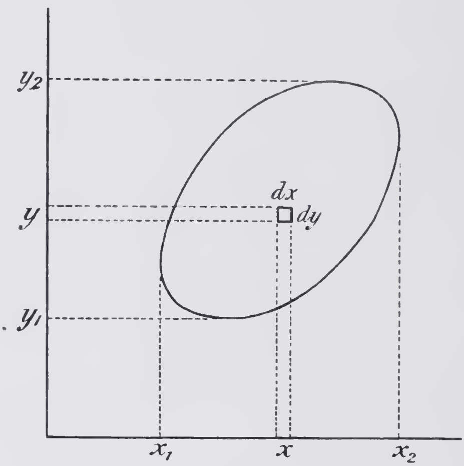


FIG. 1.

however, the current density is non-uniform over the cross-section, we have to define the resistance as follows:—

Let the conductor have a cross-section of any shape and a distribution of current density, c, over it in any manner. Then let $dx\,dy$ be an element of area of the cross-section the co-ordinates of which are x and y (see Fig. 1).

The current through the area is $c\,dx\,dy$, and if ρ is the resistivity of the material of the conductor supposed constant, then $\int_{x_1}^{x_2}\int_{y_1}^{y_2}\rho c^2\,dx\,dy$ is the expression for the total heat generated per second in unit length of the conductor.

Also the expression $\int_{x_1}^{x_2}\int_{y_1}^{y_2}c\,dx\,dy$ is the value of the total current through the conductor, x_1, x_2, y_1, and y_2 being certain limits of the area of cross-section. It is always possible to find a quantity R′ such that—

$$R'\left\{\int_{x_1}^{x_2}\int_{y_1}^{y_2}c\,dx\,dy\right\}^2=\int_{x_1}^{x_2}\int_{y_1}^{y_2}\rho c^2\,dx\,dy \quad . \quad . \quad . \quad (1)$$

and this quantity R′ may be called the resistance for non-uniform current density over the cross-section.

It can be proved by a simple application of the Calculus of Variations that under the condition that the total current is constant, R′ has a minimum value R when c is constant. In other words, that the steady resistance is the minimum resistance. In the case of high frequency currents the distribution of the current is non-uniform over the cross-section, and R′ may then be called the high frequency resistance. It is easy to show that the resistance for non-uniform current density is greater than the resistance for uniform current density without the application of any mathematics. Imagine that the cross-section of the conductor, supposed square, is divided up into elements of area, and that each filamentary conductor into which we may suppose the whole conductor thus divided has the same resistance, and carries the same fraction of the total current. Then we have equal currents density as indicated by the uniform shading in Fig. 2. Imagine that the current is removed from one filament and added to that in another. Then the total current is not altered, but the heat generated in the first-named filament becomes zero, and in the other four times what it was before. Accordingly, the total heat generation is increased, although the total current is not altered. The resistance of the conductor as above defined is therefore increased by any change in the distribution of the current which makes its density non-uniform over the cross-section. Moreover, by this mode of viewing the phenomena it is easy to see that any distribution of current density which is non-symmetrical round the periphery of the conductor is also a cause of increased resistance as compared with that corresponding to a symmetrical distribution of current density. Accordingly, not only is the resistance of a straight solid conductor greater for high frequency oscillations than for continuous currents, but the resistance of a spiral or helix of wire for high frequency currents is greater than that of the same wire when stretched out straight, because in the first case the current density is greater at the periphery of the wire than at the centre, and in the second case the peripheral distribution is non-uniform owing to the fact that the external distribution of field is non-uniform, being greater on the interior parts of the solenoid than on the outside.

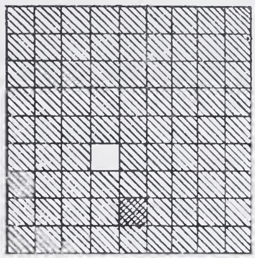


Fig. 2.

In dealing with high frequency alternating currents, we are presented in a marked degree with the phenomenon of *skin or surface concentration* of the current.

When a conductor is acted upon by an alternating electromotive force, the current does not spring into existence at all parts of the cross-section of the conductor instantly, but is created first at the surface and diffuses inwards.[2] The mathematical law according to

[2] See Stefan, *Sitzungsberichte der Wiener Akad. der Wissenschaft*, 1887, vol. 95, part ii. p. 917; also Oliver Heaviside, "Electromagnetic Theory," vol. i. p. 345, *et seq.*

which this diffusion takes place is the same as that which controls the penetration of magnetic flux into an iron bar, when it is exposed to a magnetizing force, by being surrounded by a coil through which a current is passed.

The propagation of magnetic flux through ferromagnetic substance is effected by a process which is in every way analogous to the diffusion of liquids into one another, or to the transference of temperature through a conductor—that is, as Lord Kelvin has called it, to the thermometric conductivity.[3] These two last-named processes are mathematically described by differential equations of the same form as those which determine the propagation of magnetic flux, or of an electric current into a conductor.

In the case of magnetic flux, this rate of diffusion, as Mr. Oliver Heaviside has shown, is inversely as the electric conductivity and inversely as the magnetic permeability of the material.

Consider the case of a cylinder of iron placed parallel to the lines of flux in a uniform magnetic field, say in the interior of a long solenoid traversed by a current. If we suppose the iron suddenly introduced into the uniform field, the magnetic flux seems to penetrate into it through its surface, and, so to speak, soaks more or less slowly into the mass.

A very elegant demonstration of this fact was afforded by experiments described by Dr. J. Hopkinson and Professor E. Wilson some years ago.[4] It was then experimentally proved that the application of a magnetizing force to a cylinder of iron resulted in the slow propagation of the magnetic flux into the iron from the surface inwards, and it was pointed out that the time required to establish the practically steady or uniform state of flux in the iron varies as the square of the diameter of the cylinder. Hence it follows that if the cylinder of iron, or any other conductor, is placed in a rapidly alternating magnetic field, the magnetic flux never quite penetrates to the centre of the mass of metal if its diameter exceeds a certain value. The alternation of magnetic force results in the flux, so to speak, being recalled before it has time to establish itself throughout the whole mass of the metal. A similar effect can take place with heat. If, for instance, a poker is placed in the fire, the outer surface heats up first, and after a certain time all parts of the cross-section of the poker where it is exposed to the heat come to very nearly the same temperature. If it is then removed, the outer surface cools first, but after a time it gets cool all through. If it is heated and cooled alternately and rapidly, it will be hotter on the surface than in the middle. The heat will not have time to go far in before it is compelled to return.

[3] If v is the temperature at any point having abscissa x in a thin rod which has a thermal conductivity, k, and a thermal capacity, c, then the well-known equation of Fourier which determines the temperature at any place and time is $k\frac{d^2v}{dx^2} = c\frac{dv}{dt}$, assuming the constancy of k. An identical differential equation expresses the law of diffusion of liquids or gases and the propagation of electric potential along a submarine cable as pointed out by Lord Kelvin. See *Report of the British Association*, 1888, p. 571.

[4] See J. Hopkinson, "Propagation of Magnetization in Iron," *Journal of the Institution of Electrical Engineers*, 1195, vol. 24, p. 194.

Similarly, if an electromotive force acts upon a conductor, the current begins at the surface and soaks inwards. If, therefore, the electromotive force is periodic or alternating, the current more or less is confined to the outer skin or surface of the conductor, and the higher the frequency the less does it penetrate. In the case of very high frequency currents, if the conductor is a fairly good conductor the current exists in a mere surface layer or skin. Accordingly the resistance R′ measured as above defined may have a much greater numerical value in the case of high frequency alternating currents than in the case of steady or non-periodic currents.

We have, therefore, to distinguish between the resistance to steady currents, the resistance to low frequency alternating currents, the resistance to very high frequency currents, and a fourth case presents itself when we consider damped high frequency oscillations.

The full mathematical discussion of the subject would occupy too much space. We can only indicate the mode of treatment in outline and refer the reader to various sources for additional information.

If there be any conductive medium having resistance per unit volume ρ and in which currents are being established under the action of electromotive force, then we have to consider the following variables :—

(i.) The electric current density with rectangular components u, v, w at any point in the medium.

(ii.) The electric force with components X, Y, Z.

(iii.) The magnetic force with components α, β, γ.

(iv.) The magnetic flux density or induction with components a, b, c.

The relations between these quantities will be more fully discussed in Chap. V. They are expressed in the equations, $a = \mu\alpha$, $X = \rho u$, and two similar equations in b, β, Y and v, and c, γ, Z and w, where μ is the magnetic permeability. We have then two other sets of three important equations which are called the Maxwellian equations, viz. —

$$-\mu\frac{da}{dt} = \rho\left(\frac{dw}{dy} - \frac{dv}{dz}\right), \text{ etc.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$4\pi u = \frac{d\gamma}{dy} - \frac{d\beta}{dz}, \text{ etc.} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and four other symmetrical equations in u, v, w, α, β, γ, which will be further discussed in Chap. V. They express in symbolic form Faraday's law of induction, and the fact that the line integral of magnetic force round an element of area is equal to 4π times the current through the area. Differentiating the last equation with respect to time, and remembering that there can be no concentration of current at any point, which is expressed by the relation—

$$\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz} = 0$$

we reach without difficulty an equation of the form—

$$\frac{4\pi\mu}{\rho} \cdot \frac{du}{dt} = \frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + \frac{d^2u}{dz^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and two similar equations in v and w (see Jeans, *Electricity and Magnetism*, § 535, p. 466).

These equations are identical with those first given by Fourier for the diffusion of heat into a body, and they show that the establishment of electric currents in a conductor obeys the same law of diffusion, and that it begins at the surface of a conductor and soaks inwards by a process analogous to the conduction of heat. The solution of these equations in the electrical case has been considered by Maxwell (see *Electricity and Magnetism*, vol. ii. § 690), by Oliver Heaviside (see *Electrical Papers*, vol. ii. p. 64), and by Lord Kelvin (see *Mathematical and Physical Papers*, vol. iii. p. 491), and more recently by Dr. A. Russell (see *Phil. Mag.*, April, 1909, p. 524).

Lord Kelvin gave many years ago[5] a formula by which the resistance of straight wires of circular cross-section can be calculated for alternating currents of frequency n in terms of two functions he called the *ber.* and *bei.* functions. Let d be the diameter of the wire, and ρ the steady or ordinary resistivity of the material of which it is made. Then let q denote the function $\pi d\sqrt{\frac{2n}{\rho}}$, and let the expressions *ber.* q and *bei.* q stand for the following series:—

$$ber.\, q = 1 - \frac{q^4}{2^2 . 4^2} + \frac{q^8}{2^2 . 4^2 . 6^2 . 8^2} - \text{etc.}$$

$$bei.\, q = \frac{q^2}{2^2} - \frac{q^6}{2^2 . 4^2 . 6^2} + \text{etc.}$$

Let R be the resistance to steady currents of a length l of the wire and R′ the resistance of the same to alternating currents of the frequency n; then Lord Kelvin's formula is—

$$\frac{R'}{R} = \frac{q}{2} \cdot \frac{ber.\, q\; bei.'\, q - bei.\, q\; ber.'\, q}{(ber.'\, q)^2 + (bei.'\, q)^2} \quad . \quad . \quad . \quad . \quad (5)$$

where the accents denote differential coefficients.

In Dr. Russell's discussion of the same problem he denotes the function $ber.\, q\; bei.'\, q - bei.\, q\; ber.'\, q$ by $W(q)$, and the function $(ber.'\, q)^2 + (bei.'\, q)^2$ by $Y(q)$. So that the ratio of the alternating to the steady current resistance in this notation is given by the formula—

$$\frac{R'}{R} = \frac{q}{2} \cdot \frac{W(q)}{Y(q)}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The numerical values of this ratio for various values of q were calculated for Lord Kelvin by Dr. Magnus Maclean, and are given in the table below.

[5] See *Journal of the Institution of Electrical Engineers* of London, 1889, vol. 18, p. 35, Lord Kelvin, "Presidential Address on Ether, Electricity, and Ponderable Matter."

VALUES OF $\frac{R'}{R} = \frac{q}{2} \frac{ber.\, q\, bei.'\, q - bei.\, q\, ber.'\, q}{(ber.'\, q)^2 + (bei.'\, q)^2}$

q	$\frac{R'}{R}$	q	$\frac{R'}{R}$
0·0	1·0000	4·5	1·8628
0·5	1·0000	5·0	2·0430
1·0	1·0001	5·5	2·2190
1·5	1·0258	6·0	2·3937
2·0	1·0805	8·0	3·0956
2·5	1·1747	10·0	3·7940
3·0	1·3180	15·0	5·5732
3·5	1·4920	20·0	7·3250
4·0	1·6778		

To use this table we proceed as follows:—

Consider a copper wire having a diameter, say, of 0·3 cm. and therefore a circumference $c = \pi d$ of 1·24 cm. Then for copper $\rho = 1700$ (nearly), and if we take $n = 10^5$ we have—

$$q = \pi d \sqrt{\frac{2n}{\rho}} = 1{\cdot}24 \sqrt{\frac{2 \times 10^5}{1700}} = 13{\cdot}5 \text{ (nearly).}$$

By interpolation we find that corresponding to this value of q, we have $\frac{R'}{R} = 5{\cdot}04$ (nearly), or the high frequency resistance is more than 5 times the steady resistance.

Lord Rayleigh also extended a formula, first given by Maxwell, for calculating the resistance of nearly straight conductors for alternating currents of low and high frequency when the variation follows a simple sine law.[6]

Let R be the resistance of any straight conductor of circular cross-section to steady currents, let l be its length, and μ the magnetic permeability of the material of the wire. Lord Rayleigh showed that the resistance R′ to alternating currents in terms of R and the constants can be expressed by the series—

$$R' = R\left(1 + \frac{1}{12}\cdot\frac{p^2 l^2 \mu^2}{R^2} - \frac{1}{180}\cdot\frac{p^4 l^4 \mu^4}{R^4} + \text{etc.}\right)$$

where $p = 2\pi$ the frequency n.

When dealing with non-magnetic material such as copper, for which $\mu = 1$, we have—

$$R' = R\left(1 + \frac{1}{12}\cdot\frac{p^2 l^2}{R^2} - \frac{1}{180}\cdot\frac{p^4 l^4}{R^4} + \text{etc.}\right)$$

If the conductor is a circular-sectioned uniform wire of length l and diameter d made of a material of resistivity ρ, then $R = \frac{4\rho l}{\pi d^2}$.

Hence $\frac{l}{R} = \frac{\pi d^2}{4\rho}$ and $\frac{pl}{R} = \frac{n\pi^2 d^2}{2\rho}$.

[6] See Lord Rayleigh on "The Self-induction and Resistance of Straight Conductors," *Philosophical Magazine*, ser. v., May, 1886, vol. 21, p. 381; also J. A. Fleming, "The Alternate Current Transformer," vol. i. p. 294.

Accordingly we then have—

$$R' = R\left(1 + \frac{n^2\pi^4 d^4}{48\rho^2} - \frac{n^4\pi^8 d^8}{2880\rho^4} + \frac{n^6\pi^{12}d^{12}}{58647\rho^6}\right) \quad . \quad . \quad . \quad (7)$$

Let the quantity $\frac{n\pi^2 d^2}{\rho}$ be denoted by h so that h is the product of the square of the circumference c of the round wire, the frequency and the specific conductivity or $h = \frac{nc^2}{\rho}$. The above expression (7) may then be written in the form—

$$R' = R\left(1 + \frac{h^2}{48} - \frac{h^4}{2880} + \frac{h^6}{58647}\right) \quad . \quad . \quad . \quad . \quad (8)$$

This formula for the ratio of the high frequency to the steady resistance is applicable *when h is less than unity.* The variable being, not n, d, or ρ taken alone, but the above quantity $h = \frac{nc^2}{\rho}$. It is clear that $2h$ is the same quantity as that which Lord Kelvin denotes by q^2.

The above series is, however, not suitable for the calculation of $\frac{R'}{R}$ when the value of h is greater than about 5, as it is too slowly convergent.

To meet this last case, Lord Rayleigh shows (*loc. cit.*) that the value for R′ for very high frequencies is given by the expression—

$$R' = \sqrt{\tfrac{1}{2}pl\mu R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

If S is the cross-sectional area of the conductor, then—

$$R = \frac{\rho l}{S}$$

where ρ is the resistivity or the ordinary steady specific resistance.

If the conductor has a circular section of diameter d, $S = \frac{\pi d^2}{4}$, we have—

$$R' = R\sqrt{\frac{p\mu S}{2\rho}}$$

$$\text{or} \quad R' = R\sqrt{\frac{p\mu\pi d^2}{8\rho}}$$

Furthermore, if the material of which the conductor is made is non-magnetic, then $\mu = 1$, and if it is of copper, then $\rho = 1640$ at ordinary temperatures. Hence, writing as above, h for $\frac{nc^2}{\rho}$ where $c = \pi d =$ the circumference of the wire, Lord Rayleigh's formula takes the form—

$$\frac{R'}{R} = \tfrac{1}{2}\sqrt{h} = \frac{1}{2\sqrt{2}}q = 0{\cdot}3536q \quad . \quad . \quad . \quad . \quad (10)$$

where q is the expression $\sqrt{\frac{2nc^2}{\rho}}$ as used in Lord Kelvin's formula.

If we plot the values of $\frac{R'}{R}$ given by Lord Kelvin's formula in the

above table in terms of q, we find they lie nearly on a straight line from $q = 3$ to $q = 20$ and upwards, but for $q = 0$ to $q = 1$, the value of $\frac{R'}{R}$ is nearly unity. If we plot the values of $\frac{R'}{R}$ as given by Lord Rayleigh's formula (10) we find they also lie on a straight line, inclined at a very small angle to the Kelvin line between the limits $q = 3$, $q = 20$ and upwards. Within these limits the vertical distance between the two is nearly 0·3. Hence we have the following practical rule for the high frequency resistance of round wires. Calculate for the given wire the value of q or of h. If q lies between 3 and 20 or h between 5 and 200 and upwards, then the ratio of the high frequency to the steady resistance is *very nearly* given by the semi-empirical formula—

$$\frac{R'}{R} = \frac{\sqrt{h}}{2} + 0{\cdot}3 = 0{\cdot}3536q + 0{\cdot}3 \quad . \quad . \quad . \quad . \quad (11)$$

If, however, q is less than 3 or h is small, we must employ the series given by Lord Rayleigh as in formula (8) above. Thus, for example, if we have a copper wire of circular section 1 cm. in circumference, or about $\frac{1}{8}$ of an inch in diameter, and consider a frequency as low as $n = 1000$, then $h = \frac{1000}{1640} = 0{\cdot}625$ (nearly).

Since this is less than unity, the formula (8) must be used, and we have—

$$\frac{R'}{R} = 1 + \frac{1}{123} - \frac{1}{18{,}874} = 1{\cdot}008$$

Hence the resistance to currents of this frequency is now 1 per cent. greater than its steady resistance. If, however, the frequency $n = 10^6$, then we should have $h = \frac{10^6}{1640}$ or nearly 625. Since this is vastly greater than unity we must now employ the formula (10), and since $\frac{1}{2}\sqrt{h} = 12{\cdot}5$ we have—

$$\frac{R'}{R} = 12{\cdot}5$$

or the high frequency resistance for currents of the above frequency is 12·5 times the steady resistance.

If the copper wire was only 1 mm. in circumference, equal to $\frac{1}{80}$ inch in diameter, then for a frequency of 10^6 we should have $h = \frac{100}{16} = 6\frac{1}{4}$ and $\sqrt{h} = 2{\cdot}5$, and we should have $\frac{R'}{R} = 1{\cdot}25$, or the high frequency resistance would be 25 per cent. in excess of the steady resistance. If the wire were still smaller, say, 0·1 mm. in circumference, or about $\frac{1}{800}$ inch in diameter, then h would be only $\frac{1}{16}$, and the formula (10) is no longer applicable, but we must employ (8), which gives us—

$$\frac{R'}{R} = 1 + \frac{1}{48}\left(\frac{1}{16}\right)^2 - \frac{1}{2880}\left(\frac{1}{16}\right)^4, \text{ etc.}$$

$$= 1 + \frac{1}{12{,}300}$$

Accordingly, for such small-sized wires there is no difference between the high frequency resistance and the steady resistance. In practice we may consider that for a wire as small as No. 40 S.W.G. this equality exists.

It should be noted that all the above formulæ are only applicable to straight or slightly curved round-sectioned copper or other non-magnetic wires.

A very full discussion of the formulæ for the effective resistance and inductance of circular wires has been given by Dr. A. Russell.[7] He considers the case of a concentric main consisting of one tube within another which becomes that of a simple straight solid round wire when the inner tube is solid and the outer tube of infinite radius.

Dr. Russell has given a formula for the ratio of $\frac{R'}{R}$ for the solid round wires exact for values of q greater than 6, as follows:—

$$\frac{R'}{R} = \frac{q}{2}\left\{\frac{1}{\sqrt{2}} + \frac{1}{2q} + \frac{3}{8\sqrt{2}\,q^2} - \frac{1}{2\sqrt{2}\,q^4}\right\} \quad . \quad . \quad . \quad (12)$$

$$= 0{\cdot}3536q + 0{\cdot}25 + \frac{0{\cdot}265}{q^2} - \frac{0{\cdot}35}{q^4} \quad . \quad . \quad . \quad (13)$$

where q has the same meaning as in Kelvin's formula. When q has a value of 100 or upwards Dr. Russell's formula reduces to $0{\cdot}3536q + 0{\cdot}25$, which is nearly identical with the formula (11).

Dr. Russell's formula for the resistance of a straight circular-sectioned non-magnetic wire can easily be put into the form—

$$\frac{R'}{R} = \frac{\sqrt{h}}{2} + \frac{1}{4} + \frac{3}{32\sqrt{h}} - \frac{1}{16h\sqrt{h}} \quad . \quad . \quad . \quad . \quad (14)$$

where $2h = q^2$, and if we compare this with the formula (10) given by Lord Rayleigh, viz. $\frac{R'}{R} = \frac{\sqrt{h}}{2}$, it will be seen that for large values of h the first two terms of the Russell formula are sufficient to give a close value for $\frac{R'}{R}$, and also that the formula (11) given by the author is there almost equivalent. In general, for values of h above 10 we may, for most practical cases, employ the formula—

$$\frac{R'}{R} = \frac{\sqrt{h}}{2} + 0{\cdot}25 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The above formula is of very great use in calculating quickly the high frequency resistance R′ of round solid copper wires of diameter d cms., provided that the quantity $\frac{n\pi^2 d^2}{1600}$ has a value much greater than unity, and also that the wire in question is sufficiently far from all other parts of its circuit, so that there is no disturbance of the uniform peripheral distribution of the current in it. Thus the resistance of a No. 16 S.W.G. copper wire 0·160 cm. in diameter for oscillations of frequency 10^6 is 7·4 times greater than its ordinary or steady current resistance.

[7] See Dr. A. Russell, "The Effective Resistance and Inductance of a Concentric Main and Methods of Computing the *Ber.* and *Bei.* and Allied Functions," *Phil. Mag.*, April, 1909, p. 524.

Again, consider the case of a copper rod of circular section and 1 cm. in diameter. Let the frequency of the oscillations be 10^6. We have then in the above formula (15) to put $d = 1$ and $n = 10^6$. Then $\sqrt{n} = 10^3$ and $R' = 40R$ nearly. Hence, for this frequency a thick copper rod may have an effective resistance 40 times its steady resistance. This rule, however, cannot be applied to stranded conductors, as then the current is more or less independently started in each separate strand, and the alternating resistance will be less than that given by the above formulæ for solid conductors.

We see, therefore, that in the case of thick solid wires a serious error may be committed if we neglect the difference between the high frequency alternating current resistance and the steady resistance in calculations connected with electric oscillations.

There is, moreover, a small additional increase if the high frequency currents consist of trains of *damped oscillations*. This case has been considered by Dr. E. H. Barton.[8] He takes the damped oscillation to be represented by an expression of the form—

$$i = A\epsilon^{-kpt} \cos pt \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where ϵ is the base of Napierian logarithms and k the damping factor.

In the case of simple harmonic motion, all the quantities vary, as ϵ^{jpt} where $j = \sqrt{-1}$, but for damped oscillatory motion they vary as $\epsilon^{(j-k)pt}$. If we take R'' to represent the resistance of the conductor to damped oscillations, and R as before for the steady resistance, then Dr. Barton's formula for R'' in terms of R is—

$$R'' = R\left\{1 + \frac{1+k^2}{12}\cdot\frac{p^2l^2\mu^2}{R^2} + \frac{k(1-k^2)}{24}\cdot\frac{p^3l^3\mu^3}{R_3} - \frac{1-2k^2-3k^4}{180}\cdot\frac{p^4l^4\mu^4}{R^4}\right\}$$

If we put $k = 0$ in the above expression, it becomes Lord Rayleigh's formula.

If we make p very large in the above expression, and write s for $\sqrt{1+k^2}$, and $\cot\theta$ for k, or $\cos\frac{\theta}{2} = \sqrt{\frac{\cos\theta + 1}{2}} = \sqrt{\frac{s+k}{2s}}$, we get

$$R'' = R\left(\sqrt{\frac{l\mu ps^3}{R}}\right)\cos\frac{\theta}{2}$$

but since $R = \frac{4\rho l}{\pi d^2}$, we have—

$$R'' = R\sqrt{\frac{p\mu\pi d^2}{8\rho}}(s\sqrt{s+k}) \quad . \quad . \quad . \quad . \quad . \quad (17)$$

The expression (17) only differs from that given by Lord Rayleigh by the factor $s\sqrt{s+k}$. When $k = 0$, $s = 1$, and the factor becomes unity.

The product kp is the same as that which in a previous section (see § 2, Chap. I.) we have called α, and is equal to $\frac{R'}{2L}$ for the circuit considered. Hence $k = \frac{R}{2Lp}$, or k is half the ratio of

[8] See Dr. E. H. Barton, "On the Equivalent Resistance and Inductance of a Wire to an Oscillatory Discharge," *Proc. Physical Soc. Lond.*, 1899, vol. 16, p. 409, or *Phil. Mag.*, 1899, ser. v. vol. 47, p. 433.

resistance to reactance. Also since $2n\delta = \alpha$ (see equation 3, Chap. I. § 1), where δ is the logarithmic decrement, we have $\delta = k\pi$.

Since in all cases likely to arise in practice $\frac{\delta}{\pi}$ is a small quantity of the order of 1 per cent., the correcting factor $s\sqrt{s+k}$ is also nearly unity.

The ratio of R″ to R′ is therefore generally near unity, although the ratio of R′ to R may be very large.

It is only when the semi-period decrement δ reaches a value of about 0·2 that the difference between R″ and R′ becomes important.

When we are dealing with magnetic metals this concentration of an alternating current at the surface of a conductor, or so-called *skin effect* is very marked, even for quite low frequencies.

In the case of an infinite flat plate of thickness $2h$, traversed by an alternating current of frequency n, in a direction parallel to the plane of the plate, Sir J. J. Thomson has shown that the current amplitude decreases from the surface inwards in geometrical progression as the distance from the surface increases in arithmetic progression. Also if x be the distance of any point from the surface, the rate at which the maximum values of the alternating current at successive points, taken inwards from the surface, decay is determined by a decay factor $2\pi\sqrt{\frac{\mu n}{\rho}}$, where μ is the magnetic permeability, ρ the electric resistivity, and n is the frequency.

If we consider a plate of iron for which $\rho = 10^4$ in C.G.S. units, $\mu =$ say 1000, and adopt a frequency of $100 = n$, then the decay factor is nearly 20. Hence, at a depth of 0·5 mm. from the surface, the maximum value of the current during its period will be only $\frac{1}{\epsilon} = 0{\cdot}368$ of its value at the surface, and for other depths as follows:—

Distance in millimetres of point from surface of plate.	Maximum value of the alternating current at that point expressed as percentage of the maximum value at the surface.
At surface	100·0
0·5 below	36·8
1·0 ,,	13·5
2·0 ,,	1·8
3·0 ,,	0·25

The corresponding percentage values for copper would be about 13 times greater.

Hence, in the case of iron, when employing alternating currents of a frequency of 100, the current practically penetrates only about 2 mms. into the surface. In the case of copper the practical penetration would be about 26 mms.

If, however, instead of employing alternating currents of a frequency of 100, we are dealing with electrical oscillations having a frequency expressed in millions, then the "skin" or used portion of the metallic circuit may be less than $\frac{1}{100}$ mm. in thickness.

Accordingly the specific resistance of the material of which the discharge circuit is made becomes of little consequence; the whole effects are determined by the frequency and inductance, which latter

in turn depends upon the geometric form of the circuit. An experimental proof of the above statement can be obtained by the use of the author's cymometer (see Chap. VI.).

Sir J. J. Thomson has calculated (see "Recent Researches in Electricity and Magnetism," p. 281) that for electrical oscillations having a frequency of 10^6 the thickness of the conducting skin for soft iron is about $\frac{1}{200}$ mm., and for copper about $\frac{1}{15}$ mm. In these cases there is a concentration of the current at the surface, and the outer layers of the metal are for a short time carrying current at a current density which would suffice to melt the conductor if that current density was the same at all parts of the section.

It is important to notice, however, that the formulæ which have just been given for the resistance of a wire to high frequency currents only apply to wires which are straight or bent into curves with radius of curvature large compared with the diameter of the wire. The expressions given by Lord Rayleigh (see equations (8), (9), and (10)) do not apply to spirals which are formed of turns of wire close together or wound on mandrils of small diameter compared with the diameter of the wire. The reason for this is as follows: When a wire, say, of circular cross-section, conveys a current there is a magnetic field not only outside the wire but within the wire. If the field is alternating, we must think of this interior field as composed of self-closed lines of magnetic flux which are expanding and contracting rapidly. Thus they pulsate in and out of the wire, and create electromotive forces in the wire parallel to the axis. If the closed interior lines of magnetic flux are symmetrically placed with regard to the central axis of the wire, these longitudinal electromotive forces balance each other. If, however, the interior field is not symmetrical, then there is a tendency to produce eddy currents in the wire, due to unbalanced interior electromotive forces, and these dissipate energy. Hence the energy dissipation for a given field, that is, for a given current, is greater in the case of an unsymmetrical interior pulsating magnetic field, and the wire accordingly has a greater equivalent or effective resistance. Not only, therefore, has the wire a greater effective resistance due to the concentration of the current, that is, the field, at the surface of the wire, but it may have an increase on this increase in resistance if that current distribution is unsymmetrical with regard to the axis of symmetry of the wire. This can be prevented by constructing the wire of fine insulated wires laid parallel to each other and twisted together. In all those cases in which a circuit has to be constructed, the true effective resistance of which has to be known, it is advisable not to use a round solid wire, even if we can apply to it the Rayleigh formula to ascertain its effective from its true ohmic resistance. It is better to construct the circuit or coil of stranded wire made of strands of silk- or cotton-covered No. 40 S.W.G. wire.

The cases in which we can predetermine by calculation the high frequency resistance of conductors used in radiotelegraphy are comparatively few.

Hence we are obliged to resort to actual measurements to obtain the high frequency resistance of samples of stranded cables, or metal strips, used as the circuits of radiotelegraphic apparatus.

The following apparatus was therefore devised by the author for experimentally measuring the ratio of high frequency resistance R′ to steady current resistance R. Two glass tubes, each about 75 cms. long and 3 cms. in diameter, have an expansion at the upper end and a curved bend and expansion at the lower end (see Fig. 3). The ends are provided with I.R. corks perforated by thick rods of copper, and the lower bends are filled with mercury. The upper corks are also made airtight with mercury or oil.

These tubes have side tubes blown on, by means of which they are connected by an inverted syphon of barometer tube which contains coloured water and an air-bubble in the centre to detect its displacement. This arrangement constitutes a differential air thermometer with two tubular bulbs. In these tubes are placed two identical wires, which are fastened to the copper rods passing through

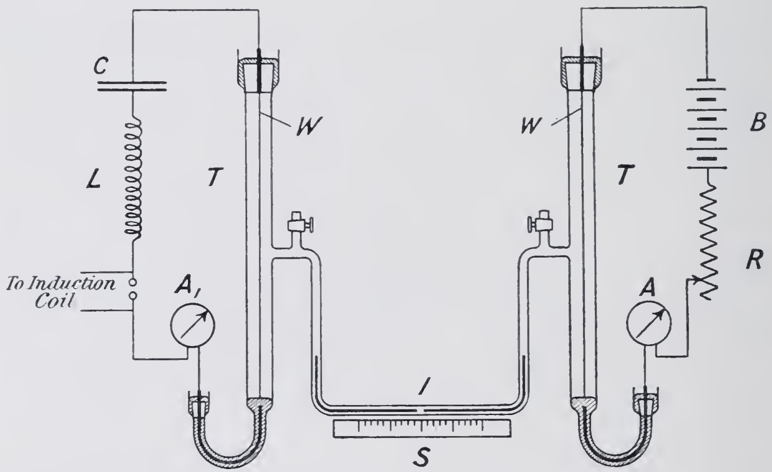


Fig. 3.—Apparatus for determining the High Frequency Resistance of Wires. (Fleming.)

the corks at the upper ends, and dip into the mercury in the bends at the lower ends. It is convenient to keep these wires in a truly axial position by one or two discs of thin mica. Suppose, then, that we pass the same electric currents through these wires in series. Both are heated and heat the air in the tubes, but if everything is symmetrical and the tubes are equally heated the bubble is not displaced. To attain this balance, however, the whole apparatus has to be placed in an enclosure, and the position of the bubble observed through a window.

If, then, we pass electric oscillations through one wire, and a steady current through the other, it is possible to adjust the steady current until the heat produced by it in one wire balances the heat produced by the oscillations in the other wire. To do this the currents have to be passed for some time, so that the thermal condition may become constant. Assuming, however, that this is the case, we have the following state of affairs. In one wire which has a resistance

R, we have a steady current A producing heat at a rate of A^2R. In the other wire of high frequency resistance R' we have oscillations of mean-square value A_1^2, producing heat at a rate $A_1^2 R'$. Since the sources of loss are the same in both cases when the final steady thermal state is reached, we have $A^2R = A_1^2R'$ or $\frac{R'}{R} = \frac{A^2}{A_1^2}$. The measurements of the mean-square value of the high frequency current must be made with a thermoelectric ammeter, such as that devised by the author (see Fig. 32 of this chapter), which is correct for high frequency measurement. There are certain points which must receive attention if accuracy in the measurement is to be attained.

First, the spark gap must be kept as short as possible, not more than 1 mm., and preferably less in length, in order to reduce the decrement of the oscillations as much as possible. The resistance of the wire for damped oscillations is greater than its resistance to undamped oscillations of the same frequency in the ratio of $s\sqrt{s+k}$ to 1, see formula (17), where $s = \sqrt{1+k^2}$ and $k = \frac{\delta}{\pi}$, δ being the decrement per semiperiod. Accordingly if δ is kept down as low as 0·04, the correcting factor will be equal to 1·007, or the resistance to damped oscillations will be only 0·7 per cent. greater than the resistance to undamped. If, however, the spark gap is large, then this correction will be large also. Again, it is necessary to employ an air blast impinging on the spark gap to keep the oscillatory current constant, and without this no good results can be obtained.[9] In general it will not be necessary to make any correction for the heat produced by the low frequency charging current of the condenser, which also passes through the wire, as the heat so produced is negligible in comparison with that produced by the oscillations.

It is necessary, however, to eliminate certain differences due to want of symmetry in the two wires by passing the oscillations first through one wire and then through the other, keeping the oscillatory current the same in the two cases, but taking the mean of the continuous currents required to effect a thermal balance in the two experiments. The results of a number of such measurements on copper wires No. 14, No. 16, No. 36 in size are collected in the Table below, which were made in the author's laboratory, and the values of their high frequency resistance, calculated by the Russell or Kelvin formulæ, are given for comparison to show how well the measured H.F. resistance agrees with the value calculated to these formulæ.

The same apparatus can be employed to examine the high frequency resistance of spiral wires, and the results of one such measurement are given for a spiral of No. 16 S.W.G. copper wire of 2·57 turns per cm. in the table. The result is to confirm the theoretical prediction that the high frequency resistance of a spiral wire is greater than that of the same wire stretched out straight.

[9] See J. A. Fleming and H. W. Richardson, "On the Effect of an Air Blast upon the Spark Discharge of an Induction Coil," *Phil. Mag.*, May, 1909, or *Proc. Phys. Soc, Lond.*, vol. 21, p. 1909.

MEASUREMENTS OF HIGH FREQUENCY RESISTANCE OF VARIOUS WIRES AND CABLES.

Conductor tested.	Value of $\sqrt{h} = \pi d \sqrt{\frac{n}{\rho}}$	Frequency n	R.M.S. value in amperes of high frequency current $= A'$	Mean value of continuous currents required to balance A' thermally $= A$	Ratio of the currents $\frac{A}{A'}$	Measured ratio of the resistances $\frac{R}{R} = \left(\frac{A}{A'}\right)^2$	Calculated value of the ratio of the resistances $\frac{R'}{R}$	Remarks.
Bare copper wire, No. 14 S.W.G. Diam. $d = 0{\cdot}203$ cm.	11·33 14·68	535,000 900,000	6·2 6·2	15·0 17·08	2·42 2·75	5·85 7·59	5·92 7·60	Calculated by the first three terms of the Russell formula, taking $\rho = 1700$.
Bare copper wire, No. 16 S.W.G. Diam. $d = 0{\cdot}1626$ cm.	8·54 8·59	475,000 485,000	7·09 7·89	15·15 16·82	2·14 2·14	4·57 4·57	4·53 4·56	Ditto.
Bare copper wire, No. 36 S.W.G. Diam. $d = 0{\cdot}0193$ cm.	1·05 1·38	510,000 880,000	1·92 1·92	1·93 1·98	1·005 1·03	1·01 1·06	1·02 1·07	Calculated value obtained by Lord Kelvin's formula.
Bare copper 2/16 cable or antenna wire	—	470,000 785,000	8·1 6·56	19·26 16·73	2·38 2·55	5·66 6·50	—	—
Bare copper cable 7/22 stranded	—	465,000 774,000	8·08 6·25	16·58 15·41	2·05 2·47	4·20 6·10	—	—
Silk covered, 19/36 Each strand insulated	—	496,000 496,000	8·46 11·00	9·93 11·70	1·18 1·06	1·39 1·12	—	—
Bare copper strip, 1·82 cms. wide 0·0147 cm. thick	—	470,000 586,000	10·60 7·57	15·92 11·28	1·5 1·5	2·25 2·25	—	—
Spiral of bare No. 16 copper wire, 142·5 turns, length = 55·4 cms. turns per cm. = 2·57	—	470,000 475,000	6·16 5·90	14·61 14·2	2·37 2·4	5·62 5·76	—	Ratio of resistance of spiral to that of same wire stretched out straight for $n = 450{,}000$ is 1·25.
Bare German silver wire, No. 17 S.W.G. Diam. $d = 0{\cdot}1422$ c.m.	1·86 1·89	463,000 475,000	7·96 6·87	9·20 7·76	1.16 1·5	1·32 1·33	1·20 1·21	Calculated value obtained by Lord Kelvin's formula taking $\rho = 26{,}600$.

One of the first to investigate this matter experimentally was F. Dolezalek,[10] who measured inductances by the bridge method of certain spirals, and found that at various frequencies between 591 and 2286, the resistance was increased and the inductance diminished compared with their steady current values. He suggested that if the coils were made of insulated wires 0·1 mm. in diameter = No. 40 S.W.G., bunched or stranded together, the effect would be annulled. The increase noticed by Dolezalek was not the difference between the value of the resistance for steady currents and that for alternating currents, but the increase over the latter due to the coiling in a spiral.

The problem was then treated mathematically by M. Wien [11] and by A. Sommerfeld,[12] who discussed Dolezalek's results and gave formulæ for calculating the increase in resistance of a solenoid due to the spiralization.

If we denote by R″ the resistance of a spiral of wire the steady current resistance of which is R, and if the resistance to alternating currents of the same frequency if the wire were stretched out straight is denoted by R′, then the formulæ of Kelvin and Rayleigh, as above given, are the values of $\frac{R'}{R}$. Sommerfeld gave a formula for $\frac{R''}{R}$ when the frequency is very high, which, in the notation used above, is equivalent to—

$$\frac{R''}{R} = 2\sqrt{\pi}\tfrac{1}{2}\sqrt{h} = 2\sqrt{\pi}\frac{R'}{R} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where h has the same meaning as in Rayleigh's formula (10). The constant $2\sqrt{\pi} = 3{\cdot}54$, and hence this formula makes the ratio of the resistance of the spiral to that of the same wire stretched out straight always 3·54 for very high frequencies and independent of the diameter of the wire or number of turns per unit of length. This does not agree with the experimental results of T. P. Black.[13] He employed two equal wires, one coiled in a spiral, and the other stretched out straight enclosed in tubes like thermometer bulbs. He measured the relative rise in temperature and heat produced in these two wires when the same high frequency current, with frequency varying between 10^6 and 5×10^6, was sent through both wires.

He found that for the spirals used the ratio $\frac{R''}{R'}$ had values between 1·20 and 1·89, or not much more than half that predicted by the formula of Sommerfeld.

A theoretical discussion and experimental examination of this question of spiral resistance has been made by L. Cohen.[14] To enable

[10] See F. Dolezalek, *Annalen der Physik*, vol. 12, p. 1142, 1903, "Ueber Präzisionsnormale der Selbstinduktion"; also *Science Abstracts*, 1904, B., *abs.* 488.

[11] M. Wien, *Annalen der Physik*, vol. 14, p. 1, 1904.

[12] A. Sommerfeld, *Annalen der Physik*, vol. 15, p. 193, 1905, "Ueber das Wechselfeld und den Wechselstromwiderstand von Spulen und Rollen."

[13] T. P. Black, *Annalen der Physik*, vol. 19, p. 157, 1906, "Ueber den Widerstand von Spulen für schnelle Elektrische Schwingungen."

[14] L. Cohen, *Bulletin of the Bureau of Standards*, Washington, U.S.A., vol. 4, No. 1, "The Influence of Frequency on the Resistance and Inductance of Solenoidal Coils."

the matter to be treated analytically the spiral was assumed to be made of square-sectioned wire, wound in one layer of closely compacted turns. The solenoid is assumed to be of considerable length so that the magnetic field within it is constant and equal to 4π times the current-turns per unit of length. He gave a general formula for the increase in resistance ΔR of one turn of the solenoid over and above the steady current resistance R which is due to frequency and spiralization as follows:—

$$\Delta R = 128N^2p^2\pi dr\sigma \sum_{x=1}^{x=\infty}\left(\frac{1}{\alpha_n x(\alpha_n^2 + \beta_n^2)}\right) \quad . \quad . \quad (19)$$

where N = number of turns of solenoid per unit of length, $p = 2\pi$ times the frequency n, d = diameter of the wire, r = interior radius of solenoid, σ = specific conductivity, and $x = 1, 3, 5, 7$, etc.

$$\left.\begin{aligned} \text{and } \alpha^2 &= \frac{m^2 + \sqrt{m^4 + 16\pi^2\sigma^2p^2}}{2} \\ \beta^2 &= \frac{-m^2 + \sqrt{m^4 + 16\pi^2\sigma^2p^2}}{2} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (20)$$

$$\text{where } m = \frac{x\pi}{d}$$

When the frequency is very high (say 10^6), the value of $16\pi^2\sigma^2p^2$ is much greater than that of m^4, and we may then take $\alpha^2 = \beta^2 = 2\pi\sigma p$, and the series part of the formula for ΔR will reduce to—

$$\frac{1}{4\pi\sigma p\sqrt{2\pi\sigma p}}\left(1 + \frac{1}{9} + \frac{1}{25} + \frac{1}{49} + \text{etc.}\right)$$

The sum of the series in the brackets is very nearly equal to 1·2, and hence to a close approximation we may write—

$$\Delta R = 38{\cdot}4N^2dr\sqrt{n\rho} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

where ρ = specific resistance, d = diameter of the wire, n = frequency, r = interior radius of the solenoid, and N = number of turns per unit of length.

Since the length of 1 turn of the wire is $2\pi r$, and the steady resistance per unit of length is $\frac{4\rho}{\pi d^2}$, we have for the total high frequency resistance per unit of length of the wire the expression—

$$\frac{4\rho}{\pi d^2} + \frac{38{\cdot}4N^2dr\sqrt{n\rho}}{2\pi r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

and hence we have a final formula—

$$\frac{R''}{R} = 1 + 4{\cdot}8N^2d^3\sqrt{\frac{n}{\rho}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

which gives us the high frequency resistance of such a single layer spiral. Suppose, for example, that a spiral is made of copper wire 2 mm. in diameter, and wound in 4 turns per cm. on a mandril 5 cms. in diameter, and subjected to oscillations of a frequency of 10^6, then we have $\rho = 1600$, $n = 10^6$, $d = 0{\cdot}2$, N = 4, $r = 5$, and—

$$\frac{R''}{R} = 1 + 15{\cdot}36 = 16{\cdot}36$$

Accordingly for this spiral and this frequency the high frequency resistance is 16·36 times the steady resistance. If the spiral were stretched out straight, then, by Dr. Russell's formula, the ratio of resistance to steady resistance would be—

$$\frac{R'}{R} = \tfrac{1}{2}\sqrt{h} + 0{\cdot}25 = 8{\cdot}1$$

Hence we have $$\frac{R''}{R'} = \frac{16{\cdot}36}{8{\cdot}1} = 2{\cdot}02 \text{ (nearly)}$$

which is not far from the ratio found experimentally by T. P. Black, and at any rate much nearer than the ratio given by the formula of Sommerfeld.

We shall, therefore, not be far wrong in saying that when a wire of anything like No. 16 or No. 18 S.W.G. is coiled into a spiral of one single layer of turns nearly in contact, the actual high frequency resistance of any considerable length of this spiral for a frequency of about 10^6 may be about double that of the same wire stretched out straight, and that this increase is due to the displacement of the interior magnetic field in the mass of the wire. It can be prevented by constructing the wire of many strands of very fine insulated wire bunched together. When the frequency is very high Cohen shows that the ratio of the resistance of the spiral to that of the same wire stretched out straight is given by the formula—

$$\frac{R''}{R'} = \frac{8N^2d^2}{\pi}\left(1 + \frac{1}{9} + \frac{1}{25} + \text{etc.}\right) \quad . \quad . \quad . \quad . \quad (24)$$

$$= \frac{9{\cdot}6N^2d^2}{\pi} \text{ (nearly)}$$

$$= 3{\cdot}06N^2d^2 \text{ (nearly)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Hence, if the turns are closely adjacent, $Nd = 1$, and $\frac{R''}{R'}$ may be as great as 3.

It is to be noticed, however, that Cohen's formula has been deduced on the assumption that there is only *one* layer of wire in closely adjacent turns, and hence does not apply if Nd is very different from unity.

2. Inductance of Conductors for Various Frequencies.—The inductance of an electric conductor may be defined to be that quality of it in virtue of which energy in a magnetic form is stored up in connection with the circuit when a current is flowing in it. Thus, if at any instant there is a current i in a circuit, the magnetic energy associated with it is represented by $\frac{1}{2}Li^2$, where L is the inductance of the conductor. It will be seen, therefore, that L and i enter into the expression for the magnetic energy of a current, just as mass, M, and velocity, v, enter into the expression $\frac{1}{2}Mv^2$ for the kinetic energy of a moving body.

It follows from this that the rate at which $\frac{1}{2}Li^2$ is changing with time is the rate at which magnetic energy is being stored up in the circuit, and must therefore be equal to the product of the current and impressed electromotive force, *less* the rate at which energy is being dissipated as heat.

Now $$\frac{d}{dt}(\tfrac{1}{2}\mathrm{L}i^2) = \frac{d}{di}(\tfrac{1}{2}\mathrm{L}i^2)\frac{di}{dt} = \mathrm{L}i\frac{di}{dt}$$

Hence if E is the instantaneous impressed electromotive force, we must have—

$$\mathrm{E}i - \mathrm{R}i^2 = \mathrm{L}i\frac{di}{dt}$$

$$\text{or}\quad \mathrm{L}\frac{di}{dt} + \mathrm{R}i = \mathrm{E}$$

$$\text{or}\quad \frac{d}{dt}(\mathrm{L}i) + \mathrm{R}i = \mathrm{E}$$

Therefore, by Faraday's law of induction, the quantity Li must represent the total flux due to the current itself, which is linked with the circuit. Accordingly we arrive at a second definition of inductance, L, which is that the inductance of a circuit is the total self-linked magnetic flux when unit current flows through the circuit.

The practical unit of inductance is called the *henry*, and one henry is defined to be the inductance of a circuit which has linked with itself a total magnetic flux of one *weber* (10^8 lines or 100,000 *kilolines*) when a current of 1 ampere flows through it.

The dimensions of an inductance on the electro-magnetic system of measurement is a *length*. Hence the absolute unit of inductance in the electro-magnetic system of measurement and in the centimetre, gramme, second system (C.G.S.) is *one centimetre*. *One henry* is equal to 10^9 cms., and hence *one millihenry* is 10^6 cms., and *one microhenry* is 1000 cms.

We shall chiefly be concerned in this treatise with small inductances which it is convenient to measure in absolute units, viz. in *centimetres* or else in *millihenrys*, or in *microhenrys*.

Another way of regarding the subject is as follows: We may think of the current in a conductor as made up of a large number of filamentary currents flowing in the same direction. These similarly directed currents attract one another. Hence to separate them all to an infinite distance, and, so to speak, take the main current to pieces, requires an expenditure of energy.

The energy which must be expended to do this is the equivalent of the kinetic energy possessed by the whole original current, and this is therefore called the potential of the current on itself. If we consider two elements of length of the circuit, viz. ds and ds', which make an angle θ with each other and are situated at a distance r, then it can be shown that the expression $\frac{ds\,ds'}{r}\cos\theta$ represents the potential energy of these elements when each is traversed by unit current. Hence to obtain the whole potential energy of the circuit with respect to itself, which is the same thing as the inductance, we have to calculate the value of the double integral $\mathrm{L} = \iint \frac{ds\,ds'}{r}\cos\theta$ for every pair of elements. The proof of this formula (due to Neumann) is given in every standard treatise on electricity and magnetism; *e.g.* "Maxwell's Electricity and Magnetism," 2nd ed. vol. ii. § 423 and § 524; also Deschanel's "Nat. Phil.," part iii., rewritten by Everett, p. 194, § 263.

In its application we have to take into account the surface or skin distribution of high frequency currents already explained. Hence when we are dealing with steady or low frequency alternating currents, the current may be considered to be uniformly distributed over all parts of the cross-section of the conductor, and the inductance calculated on this assumption is called the ordinary or low frequency inductance. If, however, we are concerned with high frequency currents, then the current is wholly concentrated on the surface or on the skin, and the inductance calculated on this distribution is called the high frequency inductance. This last is always less than the low frequency inductance.

Lord Rayleigh has given a formula for the relation between the two inductances for certain forms of nearly straight conductors.[15]

If L is the low frequency or steady current inductance of a conductor of length l, and L′ is the inductance for alternating currents of simple sine form and frequency, $n = \frac{2\pi}{p}$, then Lord Rayleigh shows (*loc. cit.*) that—

$$L' = l\left\{A + \mu\left(\frac{1}{2} - \frac{1}{48}\cdot\frac{p^2 l^2 \mu^2}{R^2} + \frac{13}{8640}\cdot\frac{p^4 l^4 \mu^4}{R^4}, \text{ etc.}\right)\right\} \quad . \quad (26)$$

where μ is the permeability of the material and R is the steady current resistance.

In the above formula A is a constant depending upon the position of the return conductor.

Lord Rayleigh also shows that when the frequency is *very* high, the above expression takes the form—

$$L' = l\left(A + \sqrt{\frac{\mu R}{2pl}}\right)$$

$$\text{or} \quad L' = lA + \frac{R'}{p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

since by (9) we have $R' = \sqrt{\tfrac{1}{2}pl\mu R}$.

When the frequency is infinite, the value of L′ tends to a limit, lA. Hence the constant A is the inductance of the conductor per unit of length for infinitely greater frequency.

On the other hand, if we put $n = 0$ or $p = 0$ in the expression (26) above, we have the value of the inductance (L) for steady or non-periodic currents. Hence—

$$L = l(A + \tfrac{1}{2}\mu)$$

$$\text{or} \quad A = \left(\frac{L}{l} - \frac{\mu}{2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

Finally, if we write L_∞ for the inductance at infinite frequency and L′ for the inductance at a high frequency, n, we have—

$$L' = L_\infty + \frac{R'}{2\pi n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

If ρ is the resistivity of the material, then $R = \frac{\rho L}{s}$, where s is the

[15] See Lord Rayleigh, "On the Self-induction and Resistance of Straight Conductor," *Phil. Mag.*, May, 1886, ser. v. vol. 21, p. 381.

cross-section of the conductor. Hence from (27) and (28) we have—

$$L' = l\left(\frac{L}{l} - \frac{\mu}{2} + \sqrt{\frac{\mu\rho}{2ps}}\right) \quad . \quad . \quad . \quad . \quad . \quad (30)$$

Furthermore, if the material is non-magnetic, $\mu = 1$, and then—

$$L' = L - l\left(\frac{1}{2} - \sqrt{\frac{\rho}{4\pi ns}}\right) . \quad . \quad . \quad . \quad . \quad (31)$$

If the section of the conductor is circular and of diameter d, then $S = \frac{\pi d^2}{4}$, and—

$$L' = L - \frac{l}{2} + \frac{l}{\pi d}\sqrt{\frac{\rho}{n}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

The formulæ (30), (31), and (32) afford means for calculating the inductance L' of a nearly straight circular-sectioned wire of length l diameter d and resistivity ρ, for high frequency currents of frequency n, when we know the low frequency inductance L.

The formula (29) gives L' in terms of the inductance L_∞ for an infinite frequency.

It is sometimes convenient to calculate L' from (29) and sometimes from (32).

If we use copper wire, $\rho = 1640$ or $\sqrt{\rho}$ is nearly 40, and then—

$$L' = L - l\left(\frac{1}{2} - \frac{40}{\pi d\sqrt{n}}\right) \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Suppose, as before, that $d = 1$ and $n = 10^6$, then the quantity in the bracket is equal to $\frac{154}{314}$, or nearly 0·5. Hence, in this case, if we deduct half the length of the wire in centimetres from the value of the steady current inductance L, we have the high frequency inductance L'.

For such circuits as are usually employed in high frequency work the difference between the two inductances is only at most a few per cent., whereas the ratio between the two resistances may be very large.

Dr. Barton has also considered the question of the inductance of a conductor under damped high frequency electric oscillations.[16] Taking into account the decay factor, he shows that the inductance L'' for simple periodic but decadent oscillations of frequency, n, is to the steady inductance L in the ratio given by—

$$L'' = l\left\{A + \mu\left(\frac{1}{2} + \frac{k}{6}\cdot\frac{pl\mu}{R} - \frac{1-3k^2}{48}\cdot\frac{p^2l^2\mu^2}{R^2} - \frac{k(1-k^2)}{45}\cdot\frac{p^3l^3\mu^3}{R^3}, \text{ etc.}\right)\right\} (34)$$

where k is the damping factor, and A, as before, has the value $\left(\frac{L}{l} - \frac{\mu}{2}\right)$. If we put $k = 0$ we have Lord Rayleigh's expression (26).

If p is very large the above expression reduces to—

$$L'' = l\left(A + \sqrt{\frac{R\mu s}{lp}}\cos\frac{\theta}{2}\right) . \quad . \quad . \quad . \quad . \quad (35)$$

where $\cot\theta = k$ and $s = \sqrt{1 + k^2}$ as before.

[16] See Dr. E. H. Barton, "On the Equivalent Resistance and Inductance of a Wire to an Oscillatory Discharge," *Proc. Phys. Soc. Lond.*, vol. xvi. p. 409, or *Phil. Mag.*, 1899, ser. v. vol. 47, p. 436.

If $k = 0$, the above expression (35) becomes identified with (27), that given by Lord Rayleigh; since, then, $\cos\frac{\theta}{2} = \sqrt{\frac{s+k}{2s}}$. As already shown, $A = \frac{L}{l} - \frac{\mu}{2}$ and $R = \frac{\rho l}{S}$. Hence we can write the above expression (35) in the case of non-magnetic materials in the form—

$$L'' = L - l\left\{\frac{1}{2} - \sqrt{\frac{\rho}{4\pi n S}(s+k)}\right\} \quad . \quad . \quad . \quad (36)$$

If the wire is circular-sectioned, $S = \frac{\pi d^2}{4}$, and we have—

$$L'' = L - \frac{2}{l} + \frac{l}{\pi d}\sqrt{\frac{\rho}{n}(s+k)} \quad . \quad . \quad . \quad . \quad (37)$$

This last equation also becomes identical with Lord Rayleigh's expression (32) when $k = 0$.

Taking the two formulæ for the high frequency resistance R′ and the high frequency inductance L′, viz.—

$$R' = \sqrt{\tfrac{1}{2}pl\mu R}, \text{ and } L' = l\left(\frac{L}{l} - \frac{\mu}{2} + \sqrt{\frac{\mu R}{2pl}}\right)$$

we eliminate μ and l and arrive at—

$$\frac{Lp - L'p}{R' - R} = \frac{R'}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

Hence, as we increase the frequency from zero to a very high value, the decrement of the reactance is to the increment of resistance in the ratio of the high frequency to the steady or zero frequency resistance. Again, if we take the same two formulæ for the high frequency resistance R′ and inductance L′, we can deduce an expression for the high frequency impedance $\sqrt{R'^2 + p_2 L'^2}$ which is often required.

For $R' = \sqrt{\tfrac{1}{2}pl\mu R}$

and $L' = l\left(\frac{L}{l} - \frac{\mu}{2} + \sqrt{\frac{\mu R}{2pL}}\right)$

If for the sake of simplicity we put $\mu = 1$, and consider only a non-magnetic circuit, then it is easy to show that—

$$R'^2 + p^2L'^2 = R^2 + p^2L^2 + \frac{R'^4 - R^4}{R^2} - 2\frac{R'}{R}(R' - R)(R' + pL) \quad (39)$$

If $R' = R$ the right-hand side reduces to its first two terms, as it should do. Accordingly, the high frequency impedance greatly exceeds the impedance for steady sinoidal low frequency currents.

3. Predetermination of Inductance for Certain Standard Forms of Circuit.—There are certain forms of circuit for which we can predetermine the inductance by calculation. Fortunately, this can be easily accomplished for one very simple form of circuit, viz. a rectangle formed of round wire, the diameter of the wire being small compared with either dimension of the rectangle. As this calculation illustrates very well the principles on which inductance generally is calculated, we shall give it in full, and then deduce certain consequences.

Suppose that two rectangles of the same size, made of infinitely fine wire, were placed with sides parallel to one another. If both are traversed in the same direction by unit current, we can calculate the potential energy M of the system by Neumann's formula, $M = \int\int \frac{dx\, dx'}{r} \cos\theta$, where dx and dx' are two elements of length in the conductors, r their distance, and θ the angle between them.

In the case of the two rectangles, θ is either 0 or $\frac{\pi}{2}$, and hence $\cos\theta$ is either 1 or 0. We have then simply to take all possible pairs of elements in the two circuits, divide the product by their distance, and sum up all these quantities. Let ABCD, A′B′C′D′ (Fig. 4) be the two rectangles. Let the distance between their planes be b, and let the length of the sides AB, A′B′, CD, C′D′ be denoted by S, and that of AC, A′C′, BD, B′D′ be denoted by S′.

We consider first a pair of elements in the sides AB, A′B′ situated

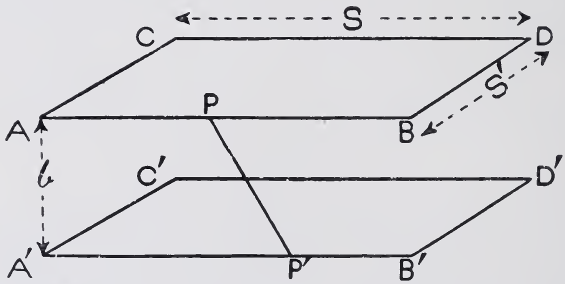


Fig. 4.—Mutual Inductance of Two Parallel Rectangular Circuits.

at P and P′. Let AP $= x$ and A′P′ $= x'$, and the length of these elements be dx and dx'. Then for this pair we have $r = \sqrt{(x - x')^2 + b^2}$ and $\cos\theta = 1$.

$$\text{Hence} \quad M = \int_0^s\int_0^s \frac{dx\, dx'}{\sqrt{(x - x')^2 + b^2}} \quad . \quad . \quad . \quad (40)$$

$$\text{Now} \quad \int_0^s \frac{dx}{\sqrt{(x - x')^2 + b^2}} = \log_0^s\left\{(x - x') + \sqrt{(x - x')^2 + b^2}\right\}$$

$$= \log \frac{S - x' + \sqrt{(S - x')^2 + b^2}}{- x' + \sqrt{x'^2 + b^2}}. \quad (41)$$

Again, it is easily proved that—

$$\int \log\{S - x + \sqrt{(S - x)^2 + b^2}\}dx$$

$$= -(S - x)\log\{S - x + \sqrt{(S - x)^2 + b^2}\} + \sqrt{(S - x)^2 + b^2} \quad (42)$$

$$\text{Hence} \quad \int_0^s \log\frac{(S - x') + \sqrt{(S - x')^2 + b^2}}{-x' + \sqrt{x'^2 + b^2}}dx'$$

$$= S\log\frac{S + \sqrt{S^2 + b^2}}{-S + \sqrt{S^2 + b^2}} - 2\sqrt{S^2 + b^2} + b^2 \quad (43)$$

But $$\frac{S+\sqrt{S^2+b^2}}{-S+\sqrt{S^2+b^2}}=\left(\frac{S+\sqrt{S^2+b^2}}{b}\right)^2 \quad . \quad . \quad . \quad (44)$$

therefore $$\int_0^s \log\frac{(S-x')+\sqrt{(S-x')^2+b^2}}{-x'+\sqrt{x'^2+b^2}}dx'$$

$$=2\left(S\log\frac{S+\sqrt{S^2+b^2}}{b}-\sqrt{S^2+b^2}+b\right) \quad (45)$$

This last expression (45) is the potential of AB on A′B′. To obtain that of AB on C′D′ we have to change b into $\sqrt{S'^2+b^2}$, and then prefix a negative sign, since then the currents are in opposite directions. We obtain thus the expression—

$$-2\left(S\log\frac{S+\sqrt{S^2+S'^2+b^2}}{\sqrt{S'^2+b^2}}-\sqrt{S^2+S'^2+b^2}+\sqrt{S'^2+b^2}\right) \quad (46)$$

Adding together (45) and (46), and doubling the sum, gives us the whole potential of the two pairs of sides of length S.

To obtain the potential of the sides of length S′ we exchange the position of S and S′ in the above final expression, and finally we obtain an expression for the whole potential energy M of the two rectangles as follows :—

$$M=4\left\{S\log\frac{(S+\sqrt{S^2+b^2})\sqrt{S'^2+b^2}}{(S+\sqrt{S^2+S'^2+b^2})b}+S'\log\frac{(S'+\sqrt{S'^2+b^2})\sqrt{S^2+b^2}}{(S'+\sqrt{S'^2+S^2+b^2})b}\right.$$
$$\left.+2\sqrt{S^2+S'^2+b^2}-2\sqrt{S'^2-b^2}-2\sqrt{S^2+b^2}+2b\right\} \quad (47)$$

To obtain the inductance of the rectangle we have to consider that b is small compared with S or S′, and we have then to substitute for b the *geometric mean distance* of all the filaments of current composing the actual current in the wire.[17] As the case considered is that of a wire of circular cross-section and a surface distribution of current, we have to take for b the geometric mean distance of all points on the circumference of a circle. This, as Maxwell shows, is a length equal to the radius $\frac{d}{2}$ of the wire section.

Making this alteration in the formula (47), we have as an expression for the high frequency inductance of the rectangle the expression—

$$L'=4\left\{(S+S')\log_\epsilon\frac{4SS'}{d}-S\log_\epsilon(S+\sqrt{S^2+S'^2})\right.$$
$$\left.-S'\log_\epsilon(S'+\sqrt{S^2+S'^2})+2\sqrt{S^2+S'^2}-2(S+S')\right\} \quad (48)$$

If we call the sides of the rectangle A and B and the diagonal $D=\sqrt{A^2+B^2}$, and use ordinary logarithms, we can write the above formula in the form most suitable for calculation, as follows :—

$$L'=9{\cdot}2104\left\{(A+B)\log_{10}\frac{4AB}{d}-A\log_{10}(A+D)-B\log_{10}(B+D)\right.$$
$$\left.-\frac{A+B-D}{1{\cdot}1513}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (49)$$

[17] For the definition of the term *geometric mean distance* (G.M.D.), see Maxwell's "Treatise on Electricity and Magnetism," 2nd ed. vol. ii. p. 298.

Let us then consider some special cases. If $S = S'$, the rectangle becomes a square, and the high frequency inductance of a square circuit of side, S, is—

$$L' = 8S\left\{\log_\epsilon \frac{4S}{d} - \log_\epsilon(1 + \sqrt{2}) + \sqrt{2} - 2\right\}. \quad . \quad (50)$$

This can be thrown into the form—

$$L' = 2l\left(\log_\epsilon \frac{4l}{d} - 2{\cdot}853\right) \quad . \quad . \quad . \quad . \quad . \quad (51)$$

where l is the perimeter of the square and d the diameter of the wire of which it is made. If we use ordinary logarithms, the formula becomes—

$$L' = 2l\left(2{\cdot}3026 \log_{10} \frac{4l}{d} - 2{\cdot}853\right). \quad . \quad . \quad . \quad (52)$$

or if S is the side of the square in centimetres—

$$L' = 8S\left(2{\cdot}3026 \log_{10} \frac{16S}{d} - 2{\cdot}853\right) \quad . \quad . \quad . \quad (53)$$

Again, if in formula (48) we put S' very small compared with S, that is, consider $\frac{S'}{S}$ can be neglected in comparison with unity, we have—

$$L' = 4S \log_\epsilon \frac{2S'}{d}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

This is the expression for the high frequency inductance of a pair of round parallel wires, each of length S, separated by a distance S', each wire having a diameter d. Let l stand for the united length (lead and return) of the two wires, each having a length $\frac{l}{2}$, and let D be their distance apart; we can put the above formula in the form—

$$L' = 2l\left(\log_\epsilon \frac{2D}{d}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

or, using ordinary logarithms—

$$L' = 2l\left(2{\cdot}3026 \log_{10} \frac{2D}{d}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (56)$$

This agrees with a formula given by Lord Rayleigh, and also by Maxwell, with the difference that they consider the low frequency inductance, and we are considering the high frequency inductance.

The two formulæ for the inductance for infinite frequency, viz.—

$$L' = 2l\left(220{\cdot}364 \log \frac{l}{d} - 2{\cdot}853\right) \text{ for a square,}$$

$$\text{and} \quad L' = 2l\left(2{\cdot}3026 \log_{10} \frac{2D}{d}\right) \text{ for a pair of parallel wires,}$$

the parallel wires being not too near and short-circuited at the far end are of great use in practice, because these circuits can easily be formed of copper wire and their dimensions accurately measured, and then the inductance for high frequency currents calculated by the above formulæ from the dimensions. Again, if we take the expression

(45) for the potential of two filamentary currents at a distance b, and put $\frac{d}{2}$ for b and l for S, we have the expression—

$$L' = 2l\left(\log_\epsilon \frac{4l}{d} - 1\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

which gives us the high frequency inductance for a circular-sectioned straight wire of length l and diameter d, the return being at an infinite distance. Also we require occasionally the value of the inductance of such a wire bent into the form of a circle, the radius of this circle being large compared with the diameter of the wire.

It is not difficult to show that the high frequency inductance L′ of this circular and circular-sectioned wire of diameter d and perimeter l is given by—

$$L' = 2l\left(\log_\epsilon \frac{4l}{d} - 2{\cdot}45\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (58)$$

$$\text{or} \quad L' = 2l\left(2{\cdot}3026 \log_{10} \frac{4l}{d} - 2{\cdot}45\right) \quad . \quad . \quad . \quad (59)$$

The proof of the above formula is given in the author's "Handbook for the Electrical Laboratory and Testing Room," vol. ii. p. 174.

It should be noted that in all these formulæ for high frequency inductance, (48) to (59), we have calculated really the inductance for *infinite* frequency (L_∞), and to obtain the true inductance for a frequency n, viz. L′, accurately, it is necessary to add to L_∞ the quantity $\frac{R'}{2\pi n}$, R′ being the high frequency resistance calculated by Lord Rayleigh's formula (9) corresponding to the frequency n considered. Generally speaking, the term $\frac{R'}{2\pi n}$ will be small compared with L_∞; hence no great inaccuracy is committed by taking L_∞ to represent the high frequency inductance.

In practical work we very frequently desire to predetermine approximately the inductance of a solenoid or spiral of one or more layers of wire, the turns being closely or not very closely packed. A very useful formula for this purpose has been given by Dr. A. Russell for the inductance (for steady currents) of a spiral of length l and mean diameter D having N turns per unit of length.[18] It is as follows :—

$$L = (\pi DN)^2 l \left\{1 - \frac{4}{3\pi}\frac{D}{l} + \frac{1}{8}\left(\frac{D}{l}\right)^2 - \frac{1}{64}\left(\frac{D}{l}\right)^4\right\} \quad . \quad (60)$$

In the above formula, if D and l are measured in centimetres and N in turns per centimetre, then L is expressed in centimetres or C.G.S. electromagnetic units of inductance. If we reckon D and l in inches and N in turns per inch, the formula becomes—

$$L = (\pi DN)^2 \frac{l}{40}\left\{100 - 42{\cdot}4\left(\frac{D}{l}\right) + 12{\cdot}5\left(\frac{D}{l}\right)^2 - 1{\cdot}56\left(\frac{D}{l}\right)^4\right\} \quad (61)$$

and still gives the inductance in centimetres.

[18] Dr. A. Russell, "On the Magnetic Field and Inductance Coefficients of Circular, Cylindrical, and Helical Currents," *Phil. Mag.*, April, 1907.

The above formula applies only to steady or very low frequency alternating currents.

In applying it to high frequency currents it needs a correction which has been supplied by L. Cohen (see *Bulletin of the Bureau of Standards*, U.S.A., vol. ii. No. 1).

The inductance of a helix may be considered to be partly due to the magnetic flux which is linked with the turns of the spiral, and partly to flux which exists within the material of the windings. The former part, for an infinitely long spiral, is given by the expression $(\pi \mathrm{DN})^2 l$, or by the complete Russell formula for a spiral not infinitely long. The part due to flux within the material of the windings is less in the case of high frequency alternating currents than in the case of steady currents. Hence the inductance for high frequency currents is less than that due to steady currents. The diminution expressed at a percentage is, however, always very much less than the increase the resistance expressed as a percentage for the same spiral and the same frequency.

The inductance of a spiral may be considered to be made up of two parts, one due to the magnetic flux linked with the turns of the spiral, and the other due to the flux within the material of the spiral. In the case of continuous or steady currents these two components of the inductance for an infinite or very long spiral have values respectively equal to $4\pi^2\mathrm{N}^2r^2l$ and $\frac{2}{3}\pi^2\mathrm{N}^2d(4r + d)l$, where l is the length of the solenoid, r its internal radius, d is the diameter of the wire of which it is made, and N the number of turns of wire per unit of length. Hence the whole inductance L for steady currents of a long solenoid is given by—

$$\mathrm{L} = 4\pi^2\mathrm{N}^2r^2l\left(1 + \frac{2}{3}\frac{d}{r} + \frac{1}{6}\frac{d^2}{r^2}\right) \quad . \quad . \quad . \quad . \quad (62)$$

The quantity in the bracket being a correcting factor for the finite diameter of the wire.

In the case of alternating currents of very high frequency (say, 10^6 or so) L. Cohen shows (*loc. cit.*) that the component of the inductance due to flux within the material of the spiral, assumed to be a spiral of one single layer of closely compacted turns of square wire, is expressed by the function—

$$64\mathrm{N}^3rdl\sum_{x=1}^{x=\infty}\frac{1}{x^2\alpha_n}\left(\frac{1}{\alpha_n^{\,2} + \beta_n^{\,2}} + 1\right) \quad . \quad . \quad . \quad (63)$$

where the letters have the signification given on p. 128.

If the frequency is very high, then $\alpha^2 = \beta^2 = 2\pi\sigma p$ and is a large quantity. Hence, as in the case of the similar formula for the resistance increase, we can say that the inductance due to the magnetic flux within the material is then equal to—

$$\frac{64\mathrm{N}^3rdl\sqrt{\rho}1\cdot 2}{2\pi\sqrt{n}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (64)$$

and the whole inductance of the solenoid of one layer of closely adjacent turns is—

$$\mathrm{L}'' = 4\pi^2\mathrm{N}^2r^2l + \frac{64\mathrm{N}^3rdl\sqrt{\rho}1\cdot 2}{2\pi\sqrt{n}} \quad . \quad . \quad . \quad . \quad (65)$$

$$= 4\pi^2\mathrm{N}^2r^2l\left(1 + 0\cdot 31\frac{d}{r}\frac{\mathrm{N}\sqrt{\rho}}{\sqrt{n}}\right) \quad . \quad . \quad . \quad . \quad (66)$$

This value of L″ is always rather less than the value of L for the same spiral.

Hence the diminution in inductance of a long solenoid of one layer due to frequency and spiralization expressed as a percentage of the steady inductance is given by—

$$\frac{100(L''-L)}{L}=\frac{100\left(1-\frac{N}{2}\sqrt{\frac{\rho}{n}}\right)}{1+\frac{3}{2}\frac{r}{d}}\text{(nearly)} \quad . \quad . \quad (67)$$

Thus, for instance, if $N=4$, $\rho=1600$, $n=10^6$, $r=5$, $d=0{\cdot}2$, we have $\frac{100(L''-L)}{L}=2{\cdot}4$, or about $2\frac{1}{2}$ per cent.

A very commonly used form of inductive circuit in radiotelegraphy is a spiral of bare or insulated wire wound on a cylinder in a single layer, or else formed into a flat spiral of a single layer.

It is necessary then to consider the predetermination of the inductance of single-layer spirals of various forms and types.

Maxwell showed that the inductance L of a circular conductor of n turns, having a rectangular section of radial depth d, and axial breadth b, and mean radius r, is approximately given by—

$$L = 4\pi rn\left\{\log\frac{8r}{R}-2\right\} \quad . \quad (68)$$

where R is the geometric mean distance of the section from itself, that is, the geometric mean of the distances between all possible pairs of elements of area into which we can divide the total cross-section. The value of $\log_\epsilon R$ for a rectangle is—

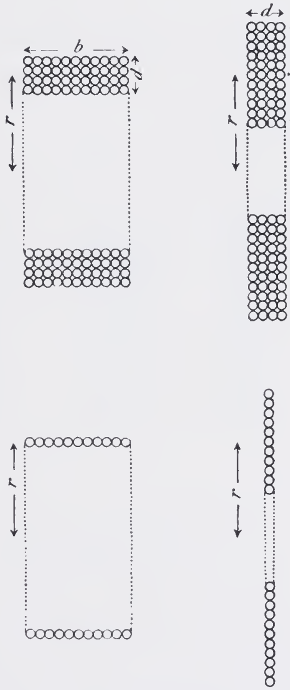


FIG. 5.—Circular Inductance Coils.

$$\log_\epsilon R=\log\sqrt{b^2+d^2}-\frac{1}{6}\frac{b^2}{d^2}\log\sqrt{1+\frac{d^2}{b^2}}-\frac{1}{6}\frac{d^2}{b^2}\log\sqrt{1+\frac{b^2}{d^2}}$$
$$+\frac{2}{3}\frac{b}{d}\tan^{-1}\frac{d}{b}+\frac{2}{3}\frac{d}{b}\tan^{-1}\frac{b}{d}-\frac{25}{12} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (69)$$

It will be seen that the expression remains the same if b and d are interchanged. Accordingly for the same mean radius and turns a coil of breadth b and depth d has the same inductance as a coil of breadth d and depth b (see Fig. 5). Hence for the same mean radius and number of turns a flat helical spiral of one layer has the same inductance as a cylindrical helix of one layer. Numerous formulæ have been given for the inductance of single layer spirals having

various discussion ratios. The expression given by Maxwell was shown by Weinstein to be not quite correct, and he gave another which was subsequently simplified by Stefan as follows :—

$$L = 4\pi r n^2 \left\{ \left(1 + \frac{3b^2 + d^2}{96r^2} \log \frac{8r}{\sqrt{b^2 + d^2}} - C_1 + \frac{b^2}{16r^2} C_2 \right) \right\} \quad (70)$$

where L is the inductance for steady currents, r is the mean radius of the coil, b is the breadth and d the depth of the section (rectangular), and C_1 and C_2 are constants which are functions of $\frac{b}{d}$ or $\frac{d}{b}$, which have been tabulated as follows :—

$\frac{b}{d}$ or $\frac{d}{b}$	C_1	C_2	$\frac{b}{d}$ or $\frac{d}{b}$	C_1	C_2
0·00	0·50000	0·1250	0·55	0·80815	0·3437
0·05	0·54899	0·1269	0·60	0·81823	0·3839
0·10	0·59243	0·1325	0·65	0·82648	0·4274
0·15	0·63102	0·1418	0·70	0·83311	0·4739
0·20	0·66520	0·1548	0·75	0·83831	0·5234
0·25	0·69532	0·1714	0·80	0·84225	0·5760
0·30	0·72172	0·1916	0·85	0·84509	0·6317
0·35	0·74469	0·2152	0·90	0·86697	0·6902
0·40	0·76454	0·2423	0·95	0·84801	0·7518
0·45	0·78154	0·2728	1·00	0·84834	0·8162
0·50	0·79600	0·3066			

The above formula is, however, obtained on the supposition that the wire is square-sectioned wire with infinitely thin insulation, and packed so as to fill up the whole of the rectangular space $b \times d$. As, however, the wire used is generally round wire with thick insulation, and does not fill up the whole space, three corrections to the above formula have to be made, which are all additive and may be combined into a single correction ΔL, so that the actual inductance is $L + \Delta L$, where ΔL has the value—

$$\Delta L = 4\pi r n \left(\log \frac{D}{d} + 0{\cdot}1386 + C\right) \quad . \quad . \quad . \quad (71)$$

The first term takes account of the fact that the wire is round and of diameter d and insulated up to a diameter D. The second term reduces from square to round section, and the third term C takes account of the difference in the mutual inductance of the various terms when the wire is of round section from that when it is of square section and having no insulation. Maxwell considered that this term C was constant and had a value $-0{\cdot}01971$, but Rosa has shown in *Bulletin* No. 3, p. 37, of the Bulletins issued by the Bureau of Standards, Washington, that C is a function of the number of layers and windings as follows :—

Turns.	Layers.	C.
2	1	0·006528
3	1	0·009045
4	2	0·01691
1	1	0·01035
8	2	0·01335
10	1	0·01276
20	1	0·01357
16	4	0·01512
100	10	0·01713
400	20 × 20	0·01764
1000	50 × 20	0·01778
Infinite	—	0·01806

The above formula and correction enables us to calculate the inductance of cylindrical or flat spiral coils, provided that the breadth b or depth d are small compared with the mean radius r.

Thus, for instance, we can employ the above formulæ to predetermine the inductance of a flat spiral of one layer and 10 turns with mean radius 10 cms., the turns being closely adjacent, and made of round copper wire insulated up to a diameter of 5 mm., the ratio $\frac{D}{d}$ being 2·6.

Then we have $r = 10$, $b = 0{\cdot}5$, $d = 5{\cdot}0$, $b^2 + d^2 = 25{\cdot}25$, $\sqrt{b^2 + d^2} = 5{\cdot}025$, $8r = 80$, $\frac{8r}{\sqrt{b^2 + d^2}} = \frac{80}{5{\cdot}025} = 15{\cdot}92$, $\log_e 15{\cdot}92 = 2{\cdot}7676$, $4\pi n^2 r = 12566$, $1 + \frac{3b^2 + d^2}{96r^2} = 1{\cdot}0026$.

Then
$$L = 12566\,(1{\cdot}0026 \times 2{\cdot}7676 - 0{\cdot}59243 + 0{\cdot}1325 \times 0{\cdot}00016)$$
$$= 12566 \times 2{\cdot}18236 = 27424 \text{ cms.}$$

also
$$\Delta L = 1256{\cdot}6\,(\log_e 2{\cdot}6 + 0{\cdot}1386 + 0{\cdot}01276) = 1382$$

and $L + \Delta L = 28806$ cms.

In order to check the accuracy of this predetermination, a flat spiral was made by winding I.R. covered $\frac{7}{22}$ wire on a flat board, as shown in Fig. 6. The total length of wire used was 628·3 cms. or 21 feet. The outside turn was 25 cms. in diameter and the inside 15 cms.

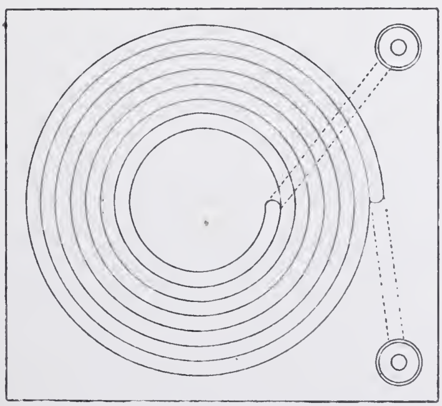


Fig. 6.—Flat Spiral Inductance Coil.

The inductance was measured with the cymometer, as follows: An oil condenser of capacity 0·00129 mfd. was joined up in series with a rectangle of wire of calculated inductance 5000 cms. The

oscillation constant of this circuit was then $\sqrt{5000 \times 0{\cdot}00129} = 2{\cdot}54$. Two similar spirals, made as above described, were then inserted in series in this oscillatory circuit, and the corrected oscillation constant found to be 8·97. Hence the inductance L of the spiral is obtained from the equation—

$$(5000 + 2\text{L}) \times 0{\cdot}00129 = (8{\cdot}97)^2 = 80{\cdot}46$$

Hence the inductance of each spiral is—

$$\tfrac{1}{2} \times (62372 - 5000) = 28{,}686 \text{ cms.}$$

Accordingly, theory predicts the inductance to be 28,806 cms., and experiment finds it to be 28,686, a difference of about one-third of 1 per cent.

Another test was made with a coil of 15 turns of $\frac{3}{22}$ wire insulated up to a diameter of 0·43 cm. Equal lengths of wire were wound up respectively into a flat helix of 15 turns, and also into a cylindrical coil of 15 turns, the mean radius in both cases being nearly 7·25 cms. and the turns closely adjacent. We have then $r = 7{\cdot}25$ cm., $n = 15$ and $b = 0{\cdot}43$, $d = 6{\cdot}5$ for flat spiral, and $b = 6{\cdot}5$, $d = 0{\cdot}43$ for cylindrical coil.

Hence
$$r^2 = 52{\cdot}56$$
$$\sqrt{b^2 + c^2} = 6{\cdot}5$$
$$\log_e \frac{8r}{\sqrt{b^2 + c^2}} = 2{\cdot}188$$
$$4\pi n^2 r = 20{,}488$$

Also for the ratio $\frac{b}{d} = \frac{d}{b} = \frac{1}{15}$ we have—

$$\text{C}_1 = 0{\cdot}562 \text{ and } \text{C}_2 = 0{\cdot}132$$

Again, $1 + \frac{3b^2 + d^2}{96r^2} = 1{\cdot}009$ for the flat spiral and 1·025 for the cylindrical coil, whilst $\frac{b^2}{16r^2} = 0{\cdot}00024$ for the flat spiral and 0·05 for the cylindrical.

Hence L = 33723 cms. for the flat spiral
and L = 34584 for the cylindrical coil.

The correction ΔL is the same in both cases. We have $\text{D} = 0{\cdot}43$, $d = 0{\cdot}15$, $\frac{\text{D}}{d} = 3$, $\log_e \frac{\text{D}}{d} = 1{\cdot}09852$, $4\pi n r = 1366$.

Therefore
$$\Delta\text{L} = 1366\,(1{\cdot}09852 + 0{\cdot}13806 + 0{\cdot}01351)$$
$$= 1366 \times 1{\cdot}25 = 1707$$

Accordingly the predetermined inductances are 35,430 cms. for the flat spiral and 36,291 cms. for the cylindrical coil.

The actual values measured as above described by the cymometer were 36,085 cms. for the flat spiral and 37,340 cms. for the cylindrical coil.

The difference in the predetermined values for the flat spiral and the solenoid of same mean radius and number of turns is due to the fact that the Stefan formula is not symmetrical in b and d, and hence does not give exact values unless b and d are both small compared with r.

The difference in the measured values is also due to a small difference, about 2 per cent., in the mean radii of the flat spiral and solenoidal coil.

The agreement, however, is sufficiently close to show that for approximate predeterminations of the inductance of flat spirals the Stefan formula can be employed with certain restrictions. Several other tests have been made confirming this conclusion.

Very convenient forms of variable inductance without sliding contacts can be made with flat spiral coil. For instance, two such spirals may be mounted on hinged boards, so as to come more or less into apposition to each other. The two spirals can be joined up in series by a flexible connection so that when the boards are shut up like a book, the currents in the two spirals oppose each other, and the joint effect is a minimum inductance (see Fig. 7). When, however,

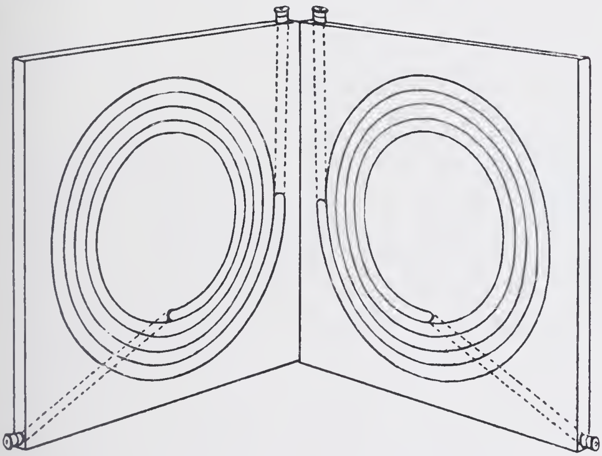


FIG. 7.—Double Flat Spiral Variable Inductance.

the boards are opened out the inductances of the two coils are added and the joint inductance is a maximum. We can, therefore, by opening the hinged boards, more or less adjust the inductance in about the ratio of 8 : 1 without altering the total resistance or introducing a rubbing contact.

We can also mount four spirals on two boards pivoted at the centre, so as to cross each other and join up these four coils, so that when the upper board is turned round through 180° the inductance varies from a minimum to a maximum value over a considerable range (see Fig. 8). Such arrangements are useful in turning coils for radiotelegraphic receivers and transmitters.

4. **The Practical Measurements of Small Inductances.**—The inductances with which we are concerned in practical high frequency work are generally small, that is, do not exceed a few thousand centimetres or a few microhenrys. Hence, methods are required for quickly and accurately determining the value of such inductances. There is no occasion to occupy space with a discussion of all the numerous methods which have been proposed for measuring

inductance. For this information the reader must be referred to text-books on electrical measurements. The author has, however, worked out in detail one very convenient method for measuring small inductances, which has been found to be most useful for this purpose.[19]

The inductive coil L, R (see Fig. 9), or circuit of which the inductance L is to be measured, is connected to a Wheatstone's Bridge, P, Q, S, in the usual way, and a plug resistance box, capable of giving a high resistance, r, is placed in the bridge circuit, together with a condenser, C, as described by Professor Anderson.[20]

The condenser may consist of one or more Leyden jars, or preferably a condenser made of sheets of ebonite coated with tinfoil

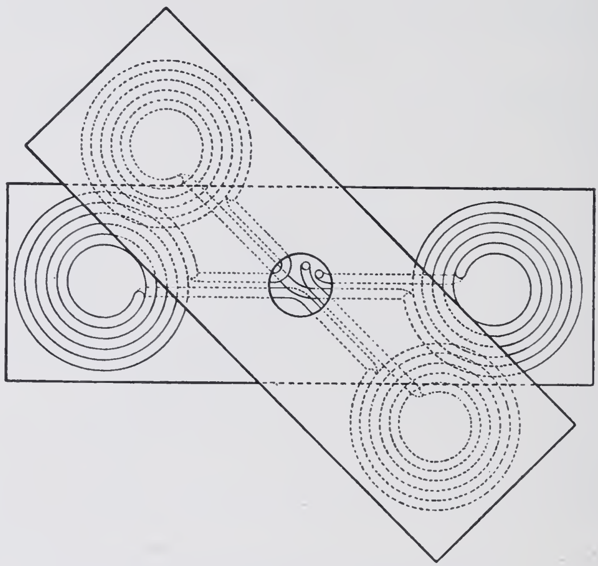


Fig. 8.—Continuously Variable Inductance.

placed in oil, and the capacity of this condenser must be very accurately determined by the method given in § 7 of this chapter. In the bridge circuit must be arranged a galvanometer, G, exchangeable with a telephone, T, and in the battery circuit (see Fig. 2) a "buzzer," Z, or device for interrupting the circuit about 250 or 300 times a second. This buzzer consists of a thin plate of iron placed over an electromagnet. There is a platinum-tipped contact point above the plate, arranged like that of an electric bell, so that when

[19] See J. A. Fleming and W. C. Clinton, "On the Measurement of Small Inductances and Capacities," *Phil. Mag.*, May, 1903, ser. 6, vol. 5, p. 492, or *Proc. Phys. Soc.*, London, vol. 18, p. 386. Also J. A. Fleming, "Note on the Measurement of Small Inductances and Capacities," *Phil. Mag.*, May, 1904, ser. 6, vol. 7, p. 586.

[20] See A. Anderson, "On a Method of Measuring Inductance," *Phil. Mag.*, 1891, vol. 31, p. 329; or *The Electrician*, vol. 27, p. 10; or J. A. Fleming, "Handbook for the Electrical Laboratory and Testing Room," vol. ii. p. 192.

the magnet is energized by a couple of secondary cells the plate vibrates rapidly. A second platinum contact is arranged on the plate, so as to interrupt the battery circuit of the bridge. The buzzer is best contained in a sound-proof box. The first step is to balance the resistance of the inductive coil L, R on the bridge for steady currents, using the galvanometer G as a detector, or else the buzzer and telephone in series may be put in the place of the galvanometer. If the resistance of the inductive coil is very low, it may be increased by adding a non-inductive resistance to it. The buzzer is next put in the battery circuit, and the telephone in the bridge circuit, and the high resistance r in the bridge circuit altered until the telephone gives no sound. If the observer has an acute ear, or obtains the assistance of some one who has, it is possible to do this with such

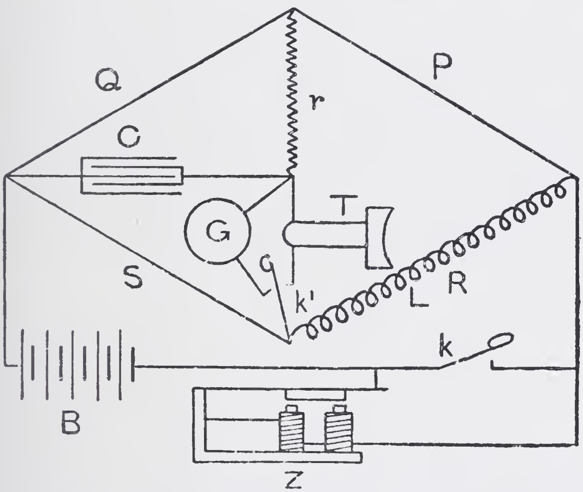


FIG. 9.—Anderson-Fleming Bridge Method of measuring Inductance.

an accuracy that a variation of 1 per cent. or less in the resistance r is detectable.

It can then be shown that the inductance L of the coil measured in henrys is given by the formula given by Anderson (*loc. cit.*), viz.—

$$L = \frac{C}{10^6}\left\{r(R + S) + RQ\right\} \quad . \quad . \quad . \quad . \quad . \quad (72)$$

where C is the capacity of the condenser in microfarads, and R is the whole resistance in the arm of the bridge which contains the inductive circuit. Since P : Q = R : S when the bridge is balanced for steady currents, and since the balance is not upset by the adjustment or introduction of the resistance r, we can write the above formula in the form $L = \frac{C}{10^6}S\left(r + r\frac{P}{Q} + P\right)$, which gives the inductance in henrys, or $L = 10^3CS\left(r + r\frac{P}{Q} + P\right)$, giving the inductance in

centimetres, the last being rather more convenient for most calculations.

The above-described method has been much used and tested by the author and his assistants in the last few years, and found to afford an excellent means for measuring inductances as small as 5 or 10 microhenrys (mhys.). It requires no apparatus that is not found or can be easily made in any electrical laboratory. The result gives us L, or the low frequency inductance of the coil or circuit. If, however, this is made of round-sectioned copper wire, the high frequency resistance, and therefore inductance, can easily be calculated from the formula already given.

As an example of the method, we may give the following instances of two measurements of inductances, one small and one very large.

The first case is that of a long helix of insulated wire, consisting of a single layer of 5000 closely adjacent turns wound on a wooden circular-sectioned rod, the mean diameter of a circular turn being 4·096 cms., and the length of the helix 200·3 cms. By the formula for the inductance of such a helix already given, we have $L = (\pi DN')(\pi DN)$, and since $N = 5000$, $D = 4{\cdot}096$, and $N' = \frac{5000}{200{\cdot}3}$, we have in this a calculated value $L = 20{\cdot}6 \times 10^6$ cms.

This helix was connected to a bridge, and had its inductance measured with a telephone and buzzer as above described. The values of the various bridge arms, bridge resistance, and the capacity were as follows :—

$P = 100$ ohms, $Q = 100$ ohms, $R = 152$ ohms, $S = 152$ ohms, $r = 217 \pm 1$ ohms, $C = 0{\cdot}256$ mfd.

Hence $L = 256 \times 152\,(217 + 217\frac{100}{100} + 100) = 20{\cdot}8 \times 10^6$ cms. The agreement is fairly close.

The second case is that of a round-sectioned copper wire 0·1994 cm. in diameter, laid round a room in the form of a square, the side of which was 607·1 cms., the ends being brought to the middle of one side and connected to the bridge. By the formula (53) on p. 136 for the inductance of such a square, we have—

$$L = 8S\left(2{\cdot}3026 \log_{10}\frac{16S}{d} - 2{\cdot}6\right) \quad . \quad . \quad . \quad . \quad (73)$$

We take 2·6 as the constant instead of 2·853, because in the measurement here made we are concerned with a low frequency inductance, and the larger value of the constant concerns the high frequency inductance.

Hence, substituting the measured values $S = 607{\cdot}1$ cms. and $d = 0{\cdot}1994$ cm., we have $L = 39{,}726$ cms.

The inductance was then measured as above, using a bridge and a condenser consisting of two Leyden jars having a total capacity together of 0·002783 mfd.

The following are the values of the bridge arms and bridge resistance :—

$P = 10$ ohms, $Q = 1000$ ohms, $R = 1{\cdot}46$ ohms, $S = 146$ ohms, $r = 92 \pm 0{\cdot}5$ ohms, $C = 0{\cdot}002783$ mfd.

$$\text{Hence } L = 1000 \times 0{\cdot}002783 \times 146(92 + 0{\cdot}92 + 10)$$
$$= 41{,}816 \text{ cms., or } 41{\cdot}816 \text{ mhys.}$$

The value calculated from first principles is 39·7 mhys., or less by 2·5 per cent. than the observed value.

The capacity of the condenser used was not probably ascertained with certainty to less than 2 per cent. Hence for such a small inductance the agreement is fairly good.

The same method is applicable to the measurement of small mutual inductances. If two coils are placed with axes in one line, they exert on each other a mutual inductance, and the current in one when varying produces an induced current in the other. The mutual inductance or coefficient of mutual inductance, M, is defined to be the numerical value of the total magnetic flux which is linked with both coils when unit electric current flows in them.

Hence, if we join both the coils in series, and call L and N the inductance or self-induction of each, and M the mutual inductance or coefficient of mutual induction, then the total flux linked with the circuit when unit current flows in it is either $L + 2M + N$ or $L - 2M + N$, according as the currents flow the same way or the opposite way in the two coils. Accordingly, if we join up two such coils as one circuit, and measure the inductance of the circuit, first with the coils joined up to add, and secondly with the coils joined so as to oppose their respective fields, and call L_1 and L_2 the apparent inductances, we have—

$$\left.\begin{aligned} L_1 &= L + 2M + N \\ L_2 &= L - 2M + N \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (74)$$

$$\text{whence} \quad M = \frac{L_1 - L_2}{4}$$

$$\text{and} \quad L + N = \frac{L_1 + L_2}{2}$$

If, then, we measure L or N separately, we have all three coefficients.

As an instance of such a measurement, we give the following :—

Two equal square coils, each consisting of 8 turns of wire, the side of each square being 64·5 cms., were placed parallel to each other and at a little distance. The inductance was then measured.

(i.) Of each coil separately $= L$ and N

(ii.) Of both coils in series, but far apart and with planes at right angles $\} = L + N$

(iii.) Of both coils so joined in series to add their fields $\} = L + 2M + N$

(iv.) Of both coils so joined in series as to oppose their fields $\} = L - 2M + N$

The values were found by the bridge method (Anderson-Fleming method) just described with the telephone and buzzer at a frequency of 256 or so. The results were —

$$L = 116{,}200 \text{ cms.}, \; N = 116{,}200 \text{ cms.}$$
$$L + N = 234{,}600 \text{ cms.}$$
$$L_1 = L + 2M + N = 287{,}800 \text{ cms.}$$
$$L_2 = L - 2M + N = 180{,}700 \text{ cms.}$$

From the last two observations we find $M = 26{,}775$ cms., and

L + N = 234,200, which agrees very well with the direct measurement of L + N = 234,600, and fairly with that of the sum of L and N separately, which is 232,400 cms.

The quantity $\frac{M}{\sqrt{LN}} = k$ is called the *coefficient of coupling*, and in the above case $k = \frac{26775}{116200} = 0{\cdot}23$. Hence the coupling would be described as *loose*, because it is less than 0·5.

The above method is easily applied to determine the mutual inductance of two coils at any moderate distance from each other, and thus to set out a curve showing the variation of mutual inductance of the coils with that distance.

Methods have been devised by the author for measuring directly the high frequency inductance and coefficient of coupling for high frequency currents of coils by means of a special instrument called a *cymometer*, to which further reference will be made later on.

This instrument enables us to determine the frequency in an oscillating circuit (see Chap. VI.).

Deferring for the present a detailed description of the appliance, we may note that since the frequency of an oscillating circuit is given by the formula—

$$n = \frac{5 \times 10^6}{\sqrt{CL'}}$$

where C is the capacity of the condenser in it in microfarads, and L′ the high frequency inductance in centimetres, we can determine L′ if we know C and n. The cymometer enables us to measure the frequency n, and then, assuming the capacity of the condenser used can be measured independently, we calculate L′ by the formula—

$$L' = \frac{25 \times 10^{12}}{Cn^2}$$

where C is measured in microfarads and L′ is given in centimetres.

The process of measurement consists in placing the coil, the inductance of which is required, in series with a spark gap and a condenser, say a Leyden jar, of known capacity, and by means of an induction coil exciting electric oscillations in the circuit. The frequency of these oscillations being measured by the cymometer or other means, we have the value of n, and therefore of L′.

In one form of cymometer the measurement actually made is the wave length of a stationary electric oscillation set up on a long helix of wire. The velocity with which this wave travels along the helix can be determined from the calculated inductance and measured capacity of the spiral per unit of length. For the particular helix with which the measurements below given were made, this velocity was found to be 175×10^6 cms. per second. The process of measurement consists in attaching the helix either directly or with the interposition of a small air condenser to an oscillation circuit constructed with a known capacity and with the inductance to be determined, and then adjusting a sliding metal saddle on the helix in such a position that when the saddle is connected to earth the section of the helix between it and the oscillatory circuit is one complete wave length of a stationary electric wave on the helix. The quotient of

wave velocity along the helix by this stationary wave length then gives us the frequency n of the oscillatory circuit (see Chap. IV. § 1).

The self and mutual inductances of an oscillation transformer were measured for a frequency $2{\cdot}5 \times 10^6$ as follows: The primary coil consisted of one turn of stranded copper wire nearly 1 metre in length bent into the form of a square. Its inductance, L, was determined by finding the oscillation frequency as above described, when this coil was associated with a condenser having a capacity of 0·005835 mfd. to form an oscillatory circuit. The wave length on the cymometer helix was found to be 71 cms., and hence the frequency was $\frac{175 \times 10^6}{71}$, and this must be equal to $\frac{5 \times 10^6}{\sqrt{0{\cdot}005835L'}}$ where L' is the inductance of the primary coil in test. Hence $L' = 719$ cms.

In the same way the total inductance of the primary and secondary was determined for the two modes of connection and found to be—

$$\begin{aligned} L_1 &= L + 2M + N = 57{,}933 \text{ cms.} \\ L_2 &= L - 2M + N = 45{,}384 \text{ cms.} \\ \text{whence} \quad M &= 3137 \text{ cms.} \\ \text{and} \quad L + N &= 51{,}658 \text{ cms.} \end{aligned}$$

Deducting the separately measured primary inductance, viz. 719 cms., from $L + N = 51{,}658$ cms., we have the secondary inductance 50,940 cms., or nearly 51,000 cms.

A separate and independent measurement of the inductance N of the secondary circuit gave the value $N = 52{,}600$.

The difference between 52,600 and 51,000 is about 3 per cent., but the length of the stationary wave on the helix is hardly certain to 1 per cent., and the inductance varies as the square of the wave length on the helix. Hence the percentage error of the wave length is doubled in calculating the inductance.

From the above figures, we find the *coefficient of coupling* $k = \frac{M}{\sqrt{LN}}$ for this transformer to be—

$$k = \frac{3137}{\sqrt{719 \times 51{,}000}} = 0{\cdot}52 \text{ (nearly)}$$

Hence the coupling is *close*, because k has a value greater than 0·5.

Another confirmation of the accuracy of this last method was obtained by measuring the inductance of a single copper wire 0·1994 cm. in diameter bent into the form of a square having a side of length 607·1 cms. The frequency used was about 10^6. Associating this square inductance with a capacity of 0·00146 mfd., the cymometer determined the frequency of the oscillations set up in this circuit to be $\frac{175 \times 10^6}{264}$, and this by the general formula, viz. $n = \frac{5 \times 10^6}{\sqrt{CL}}$, gives us a value for L of 39,970 cms. as the inductance of the square.

The inductance calculated from the length of side of square = S and diameter of wire = d by the formula—

$$L = 8S\left(2{\cdot}3026 \log_{10}\frac{16S}{d} - 2{\cdot}85\right)$$

is 38,562 cms. Hence the two are in very fair agreement.

For additional information on the measurement of small inductances by means of electric oscillations the reader is referred to a paper by Mr. H. H. Taylor, in the *Physical Review* for October, 1904, vol. xix. p. 273. Taylor employed a resonance method in which the inductance to be measured has its value determined by substituting for it an equivalent inductance obtained by sliding a slider along two parallel wires. The inductance per unit of length of the parallel wires can be calculated, and hence if the effective length of the parallel wires is altered by moving the slider, the addition to their inductance becomes known.

The arrangement is shown in Fig. 10. An oscillating circuit is set

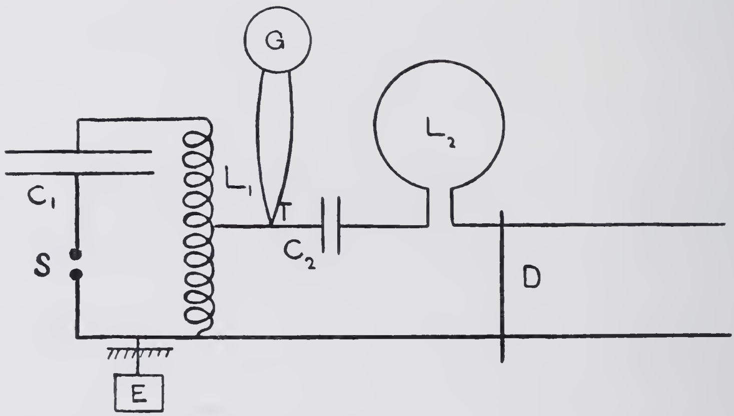


Fig. 10.—Taylor's Method of measuring High Frequency Inductance.

up consisting of a capacity, C_1; an inductance, L_1, which is preferably variable; and a spark gap, S. One point on this circuit is earthed at E. To two adjacent points on L_1 near the earthed end a pair of parallel wires are connected, and in the run of one of these is inserted a condenser, C_2, and the inductance, L_2, to be measured. A slider, D, can be moved along the parallel wires. The measurement consists in moving D to two positions, one with the inductance L_2 short-circuited, and adjusting the position of D so that the maximum current flows in the parallel wires, as shown by the maximum deflection produced on a galvanometer, G, when connected with a delicate thermo-electric junction, T, attached to some point on the parallel wires.

This method is simple, and seems capable of considerable accuracy. It can be checked by using for L_2 a single wire bent into the form of a circle or square. It has the advantage that no special apparatus is necessary. The only limitation is that the method is not applicable to inductances whose resistances vary so widely as to affect seriously

the period of the auxiliary circuit unless a compensating inductionless resistance is inserted to swamp any difference in the resistances of the inductances compared.

For a description of another form of direct-reading cymometer devised by the author for making high frequency measurements of capacity and inductance, the reader is referred to Chap. VI., § 15, of this treatise.

5. Inductance Coils of Variable Inductance.—In practical work on electric oscillations or Hertzian wave telegraphy, we often require to insert in circuits inductances which can be varied gradually or by steps. Arrangements for effecting this are called inductance boxes or sliding inductances. In some cases the change in inductance must be gradual and not accompanied by any change in the resistance, in other cases a slight change in resistance is not of moment. For varying the inductance of a circuit within certain narrow limits without making any break in the circuit or change in its resistance, a very convenient arrangement is one introduced by the author, called an *accordian coil* or *concertina coil*, from its rough resemblance to these musical instruments.

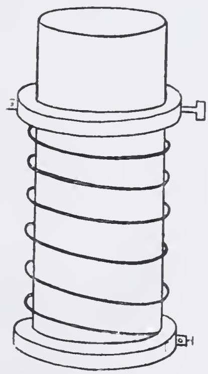


Fig. 11.—Variable Accordian Coil Inductance. (Fleming.)

On a tube of vulcanized fibre is placed a couple of rings of wood, one of them fixed at the end of the tube and the other sliding on the tube (Fig. 11). This last ring can be clamped by a screw in any position. The rings are connected by a spiral wire of brass or hard drawn copper, which is covered with indiarubber or otherwise insulated. When the rings are near together this wire is arranged in a close spiral with the turns in one layer and touching. When the rings are moved far apart the turns of the wire are widely separated, and the inductance has then a minimum value.

By sliding the movable ring to various positions, the inductance can be given any value within certain limits. When a small accompanying change of resistance does not matter, the following arrangement due to the author is effective.[21]

On a boxwood cylinder, about 10 cms. in diameter and 100 cms. in length, a screw groove is cut, the grooves being separated by at least 5 mm. This cylinder is mounted with brass end plates and held in bearings. A winch handle serves to rotate it (see Fig. 12).

In the groove is wound a bare thick copper wire, say No. 12 or No. 14 S.W.G., and the ends of the wire are soldered or screwed to the end plates on this cylinder. Against one end plate a spring contact with terminal on it presses.

Parallel with the cylinder is fixed a thick brass rod, and on this travels a contact piece, the end of which makes contact with the copper wire. A weight on this contact serves to keep a good electrical connection. When the cylinder is turned, the contact piece slides

[21] See J. A. Fleming, "On a Standard of Small Inductance," *Phil. Mag.*, May, 1904, p. 592.

along and interposes a variable number of turns of the wire between the end contact on the cylinder and the moving contact on the wire. Hence the inductance between these points can be varied.

In employing such an inductance with high frequency currents, it should be noted that as there is always a certain dielectric current between the turns of wire, which acts to diminish the effective inductance, and it must not be assumed that such a bare spiral inductance has exactly the same inductance for high frequency currents as for low frequency currents, apart altogether from the variation of distribution of current over the cross-section of the wire. The inductance

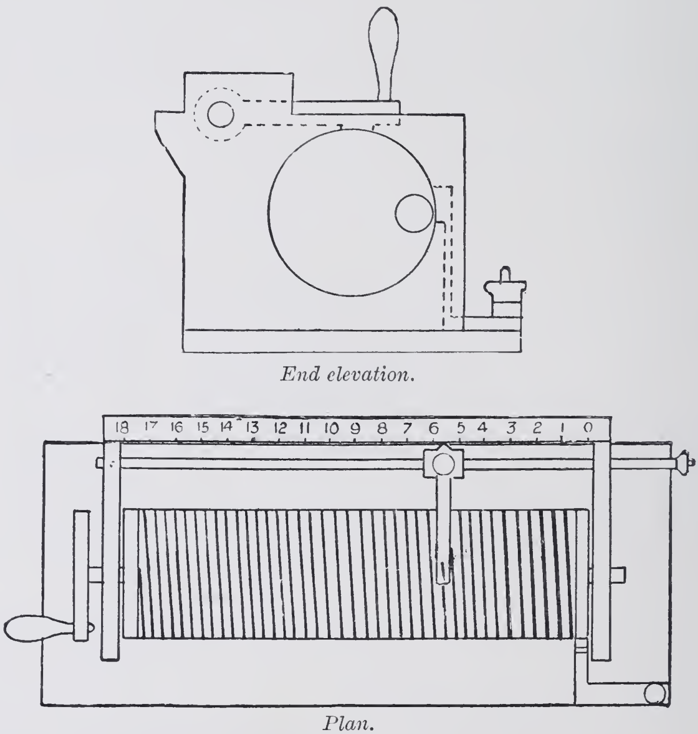


Fig. 12.—Variable Inductance Coil. (Fleming.)

for high frequency currents will always be less by a somewhat uncertain amount owing to this dielectric current between the turns.

When a small variation is required, a couple of bare wires may be stretched parallel to each other, and a sliding metal connecting piece laid across them and moved along. The same remarks, however, as above apply in this case. The dielectric current across from wire to wire prevents us from determining exactly, either from this calculated value or a low frequency measurement, the true inductance when high frequency currents are employed with it. Nevertheless, when the inductance is not required to be known very accurately the arrangement is convenient.

In the case of larger inductances it is convenient to be provided with a number of glass or ebonite rods, on which is wound silk-covered copper wire in one layer, the turns close together. The length of the rod must be at least 20 times, and preferably 50 times, its diameter, and then the inductance can be approximately calculated from the Russell formula—

$$L = (\pi DN')^2 l \left\{1 - \frac{4}{3\pi}\frac{D}{l} + \frac{1}{8}\left(\frac{D}{l}\right)^2 - \frac{1}{64}\left(\frac{D}{l}\right)^4\right\} \quad . \quad . \quad (75)$$

where N is the total number of turns, l the length, D the diameter, S the cross-section of the rod, and N′ the number of turns per unit of length of the helix, all measurements being in centimetres or square centimetres.

When the dimension ratio is at least 50 : 1, the inductance predetermined by the simple formula $L = (\pi DN')^2 l$ will not differ from the actual inductance by more than 2 or 3 per cent., as shown by the comparison between the so calculated value of a coil used by the author, and its inductance repeatedly measured by the bridge (Anderson-Fleming) method.

Results of Inductance Measurements of a Long Coil, having a Dimension Ratio of 50 : 1.

P.	Q	R.	S.	r.	C. in mfds.	L. observed in cms.	
100	1000	152·26	1522·2	4260	0·00272	19,900,000	A
100	1000	152·31	1523·1	7675	0·00149	19,400,000	A
100	1000	151·1	1511	4400 ± 50	0·00272	20,300,000	B
1000	10,000	151·5	1515	3350 ± 50	0·00272	19,200,000	B
100	10,000	151·5	15150	365 ± 5	0·00272	19,300,000	B
1000	1000	152	152	24,200 ± 100	0·00272	20,100,000	B
100	1000	151·4	1514	4400 ± 50	0·00272	20,300,000	B
1000	10,000	151·4	1514	3330 ± 20	0·00272	19,200,000	B
10	1000	151·7	15170	485 ± 5	0·00272	20,600,000	B
100	10,000	151·7	15170	365 ± 5	0·00272	19,300,000	B
100	100	152	152	217 ± 1	0·256	20,800,000	B

Mean of A readings = $19{\cdot}7 \times 10^6$ cms.
Mean of B readings = $19{\cdot}9 \times 10^6$ cms.
Value calculated from the formula $L = (\pi DN)(\pi DN') = 20{\cdot}6 \times 10^6$ cms.

In connection with the question of standards of small inductance it should be pointed out that Mr. A. Campbell has advocated the use of standards of mutual inductance for the following reasons [22] :—

(*a*) The absolute values can be calculated with much more certainty from the geometrical dimensions, since the formulas for mutual inductance are of high theoretical accuracy while those for self inductance are much less satisfactory.[23]

(*b*) Unless the conductors are highly stranded, the current distribution varies with frequency, and in general the self inductance will also vary. By keeping the two circuits at a relatively large

[22] "On the Use of Variable Mutual Inductances," A. Campbell, *Proc. Phys. Soc. Lond.*, vol. xxi. p. 69, 1908.

[23] For example see Rosa, *Bull. Bur. Stands.*, vol. ii. p. 161, 1906; and Strasser, *Ann. der. Phys.*, vol. xviii. p. 763, 1905.

distance from one another the mutual inductance is practically free from this effect.

(*c*) The effects of distributed capacity are probably less in mutual than in self inductances. In all cases the distributed capacity of one of the two coils can be made very small by sufficiently decreasing the number of turns in it (or opening them apart) while increasing the number in the other coil to keep the M constant.

When the mutual inductance is of the variable type, it can always be designed so that its value can be varied continuously from *negative to positive through zero.* This is a very great advantage, for with variable self inductance standards the incapability of reaching a zero value is a distinct drawback.

He has therefore designed a variable inductance made as follows; the description being taken, by permission, verbatim from his Paper (*loc. cit.*).

The general arrangement of the apparatus is shown diagrammatically in Figs. 13 and 14, which are plan and side view respectively. The primary circuit consists of two equal coaxial coils C and C′

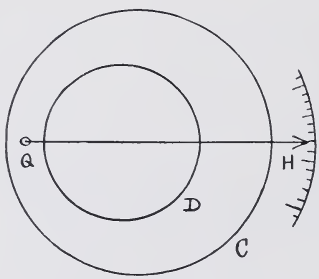


Fig. 13.

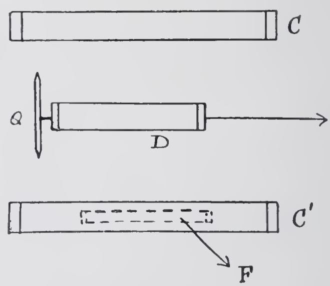


Fig. 14.

which are connected in series, their windings being in the same direction of turning. The secondary consists of the coils D and F in series. Of these coils, D is movable, being mounted on an eccentric axis Q so as to be free to turn in a plane parallel to those of C and C′ and midway between them. Rigidly connected with the movable coil is a pointer, H, which moves over a circular scale of about 180° in extent and graduated to read directly. The coil F is subdivided into ten sections, which are in series, each of them being 0·1 millihenry, and their junctions are brought to a set of separate terminals or studs with a turning head. The range of the moving coil extends from − 0·002 to + 0·11 millihenry. This gives a continuous range from 0 up to 1 millihenry, readable near zero to 0·02 microhenry, to 1 part in 500 at 0·1 millihenry, and to 1 in 5000 at 1 millihenry. The subdivision of the coil F is easily carried out by the following artifice. The coil is wound with uniformly stranded wire of ten insulated strands, all the strands are connected in series, and the whole adjusted to give 1 millihenry. If the stranding has been properly done, it will be found that no one of the sections differs from its neighbours by more than 1 part in 1000, and each is 0·1 millihenry. The placing of the movable secondary coil midway between the planes of the two

primary ones ensures that small axial displacements shall have very little effect on the mutual inductance.

The equality of any pair of sections can be tested by connecting them in series with their windings in opposition in circuit with a ballistic galvanometer and reversing the current in the primary. It should be noticed here that, if a primary coil have any number of secondary circuits, the mutual inductance to all the secondaries in series is equal to the algebraic sum of their separate mutual inductances (+ or − according to the direction of the winding). Owing to this very important property we can build up and step down in the values as easily as if we were dealing with resistances, and there is the further simplification that we can subtract as well as add the values. The marking of the scale and the setting of the coil F are done by comparison with a fixed standard mutual inductance of the kind devised by Mr. Campbell.[24] The comparison may be made by Maxwell's method, but using a sensitive ballistic galvanometer or a vibration galvanometer as detector. When a vibration galvanometer is used as in Fig. 15, it should be remembered that, for a balance, *two* conditions must be satisfied, viz.—

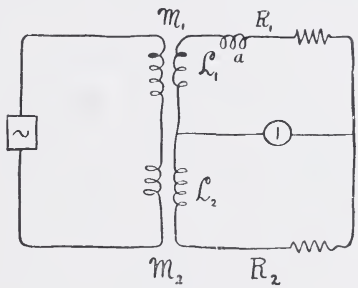


FIG. 15.

$$\frac{M_1}{M_2} = \frac{R_1}{R_2}$$

and
$$\frac{L_1}{L_2} = \frac{R_1}{R_2}$$

where R_1 and R_2 include the resistances of the secondary coils. In order that the second condition may hold, it is necessary to introduce into one of the secondary branches a coil *a* whose self-inductance can be continuously varied; by alternate adjustments of $\frac{R_1}{R_2}$ and the self-inductance of this coil, a balance is easily obtained. The fact that R_1 and R_2 are partly of copper coils is apt to introduce some inaccuracy. The copper resistance, however, can usually be largely swamped without losing too much of the sensitivity.

Any unknown mutual inductance, whose value lies within the range of the variable standard, can be at once determined by connecting the primaries of the unknown and the variable in series to B (Fig. 16), a source of alternating or intermittent current, while the secondaries, with their windings in opposition, are connected in series to a vibration galvanometer G. The

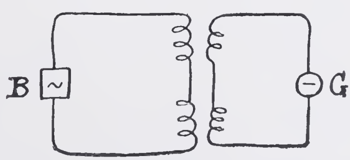


FIG. 16.

[24] *Phys. Soc.*, May, 1907; *Phil. Mag.* [6], vol. xiv. p. 494, Oct. 1907. Also see *Proc. Roy. Soc. A.*, vol. lxxix. p. 428, June 5, 1907.

variable M is then adjusted to bring the deflection to zero, and the reading gives directly the value of the unknown M. This is an extremely simple method, as it involves no knowledge of any resistances. A ballistic galvanometer and a commutated current may be used. This method, does not apply to mutual inductances higher than the maximum value of the variable standard. The standard of mutual inductance can then be used to measure a self-inductance as follows:—

In Fig. 17 let a variable mutual inductance M whose *primary* includes the subdivided coil be connected into a Wheatstone's network, as shown, along with a self-inductance L_2. Let the resistances of the arms be P, Q, R, and S respectively, the self-inductance of the arm P being L_1 (the secondary coils of M) and that of Q being L_2. Let H be a source of periodic current, and G a vibration galvanometer tuned to resonance with it, so that we may take the wave form of the currents to be a sine curve. Let the instantaneous potentials of the three upper corners be v_1, 0, and v_2 respectively, and the instantaneous values of the currents into the upper corner be i_1, i_2, and i as marked. Let $p = 2\pi n$, where n is the frequency, and for convenience of writing let $p\sqrt{-1}$ be denoted by a, so that $a^2 = -p^2$. The mutual inductance M may be made positive or negative according to the way in which the coils are connected; and in all that follows we might write $\pm$ M for M throughout. When the galvanometer shows a balance, $v_1 = v_2$, and the instantaneous value of the current through G is zero.

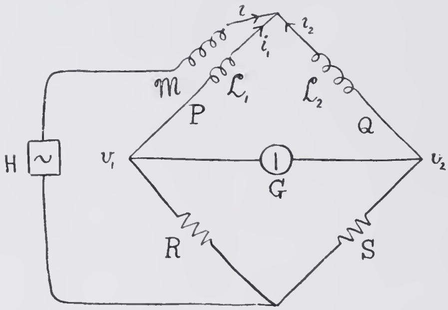


FIG. 17.

Also

$$i = -i_1 - i_2$$

Accordingly we may write—

$$(P + L_1 a)i_1 - Mai = (Q + L_2 a)i_2$$

therefore

$$[P + (L_1 + M)a]i_1 = [Q + (L_2 - M)a]i_2$$

also

$$Ri_1 = Si_2$$

Hence

$$S[P + (L_1 + M)a] = R[Q \,.\, (L_2 - M)a]$$

Equating the real and imaginary parts each to zero, we have—

$$SP = QR \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (76)$$

and

$$S(L_1 + M) = R(L_2 - M) \quad . \quad . \quad . \quad . \quad . \quad . \quad (77)$$

Exactly the same equations hold when the positions of the source and the galvanometer are interchanged.

The most useful case is when the non-inductive arms are made equal, *i.e.* $S = R$; then (76) and (77) become—

$$P = Q$$

$$\text{and} \qquad L_2 - L_1 = 2M \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (78)$$

This case gives an extremely convenient way of measuring small self-inductances, which is done as follows:—

The arrangement is shown in Fig. 18. The non-inductive arms are equal (R, R). In the arm AB there is the secondary coil *a* of self-inductance L in series with a practically non-inductive rheostat *r*. In the arm AC is placed a "balancing" coil *b* also of self inductance L and of resistance equal to or slightly greater than that of *b*. By adjusting *r* the bridge will balance when $M = 0$. The small self-inductance N to be measured is now inserted in series with coil *b* in arm AC, and a balance obtained by altering *r* and M. Then, by (78), $N = 2M$. Thus N is found directly from the reading of M, and the range of values that can be measured runs from 0 up to twice the highest reading of the variable mutual inductance. [For values of N above this range the more general case (equations (76) and (77)) may be used.] The L's of the coils *a* and *b* should be adjusted to equality once for all by putting M at zero and setting one of the coils. An exact setting is convenient, but not necessary, for if L_a and L_b differ slightly, they can be balanced (without N) by a small reading M_0. If M be the reading for balance when N is inserted, then $N = 2(M - M_0)$.[25]

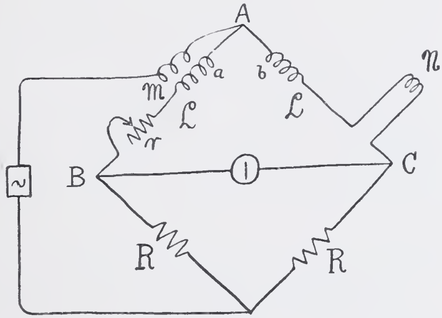


FIG. 18.

Even if *a* and *b* are well matched, it is always well to begin by reading their difference if any.

It will be noticed that the method is really a differential one; when N is introduced into the arm AC no alteration has to be made in the other arms except to increase the resistance of AB by an amount equal to the resistance of the coil N. But although it has *all the advantages of differential measurement, the reading can be made to give* N *directly* without having to take a difference at all. This is due to the use of the inductive balancing coil *b*.

The method has the advantage that it does not require the knowledge of the absolute value of any resistance. The non-inductive bridge arms must be equal; to check the equality they can be interchanged. For the non-inductive adjustable resistance *r* it is best to employ a special rheostat consisting of two slightly

[25] If coil *b* be made non-inductive we revert to Maxwell's method of comparing the M of a pair of coils with the L of one of them. Equation (77) then reduces to $\frac{L}{M} = -\left(1 + \frac{R}{S}\right)$. Maxwell, "Elect. and Mag.," 2nd edit. vol. ii. § 756.

flattened thin wires running parallel to one another at a few millimetres' distance, with a sliding contact piece across them to complete the circuit. The inductance of such a rheostat can be approximately calculated, and may thus be allowed for when measuring very small self-inductances. The inductance of the part added to compensate for the introduction of N has merely to be subtracted from the result.

In practice the method proves very convenient; with the variable mutual inductance described above, self-inductances of any value from 0·1 microhenry up to 2000 microhenrys can be measured directly without the bridge being altered in any way except in the rheostat r. In a later model the whole scale of the movable coil corresponds to 20 microhenrys, and at this value it can be read to 1 or 2 in 1000—at 200 microhenrys to 1 or 2 in 10,000. All the resistances of the coils are very low, and the sensitivity can be considerably increased by using M. Wien's method of connecting the vibration galvanometer to the bridge by means of a transformer of suitable ratio $\left(\frac{n_1}{n_2} \text{ small}\right)$. The method will also give the difference between two unknown self-inductances introduced into AB and AC.

6. Electrical Properties of Dielectrics. Dielectric Strength.—We have next to consider the special properties of dielectrics, especially those which are important in connection with high frequency phenomena.

When a dielectric or insulator is subjected to electric force, it has produced in it electric strain or electric displacement, just as a ferromagnetic body, when submitted to magnetic force, has the state called magnetization produced in it. There is, however, a great physical difference between the two phenomena. If the electric force rises beyond a certain limit, the dielectric is mechanically ruptured or destroyed at some place, and this is accompanied by a transformation of some, at least, of the potential energy of the electric strain into heat and light or mechanical motion. In the case of liquids and gases, the wound so created is self-healing, and the dielectric restores itself at that point to the original state as soon as the electric force is diminished. In solids this, however, is not done, so that the result of the operation is to leave a puncture or hole. The electric force corresponding to which this rupture or puncture takes place is called the *dielectric strength* of the insulator, and is measured in absolute units of electric force, or in its equivalent in volts or kilovolts per centimetre. It is convenient sometimes to state it in *volts per millimetre*, since the thickness of layers of dielectric used is generally expressed in millimetres. Since one electrostatic unit of potential in C.G.S. measure is equal to 300 volts, we convert kilovolts per centimetre into its equivalent electric force expressed in electrostatic units by multiplying by 3·333.

This dielectric strength depends upon (1) the thickness of the dielectric, thin layers being apparently stronger than thick; (2) it varies with the form of the conducting surfaces opposed, and (3) with the manner in which the electric force is applied, that is, whether gradually, suddenly, steadily, or periodically varying.

According to the investigations of C. Baur, every dielectric,

whatever its thickness, requires a certain voltage to puncture it, which is proportional to $t^{\frac{2}{3}}$ where t is the thickness.

Hence, if V is the puncture voltage—

$$V = Ct^{\frac{2}{3}}$$

where C is some constant.[26]

The above formula may be put in the form—

$$\frac{V}{t} = \frac{C}{\sqrt[3]{t}}$$

Hence the dielectric strength $\left(\frac{V}{t}\right)$ should vary inversely as the cube root of the thickness. Therefore, according to this formula, to puncture a sheet of dielectric 9 mms. thick would require only half the voltage per millimetre that is necessary to puncture a sheet of the same dielectric 1 mm. thick. In other words, a thin sheet of any dielectric is relatively stronger than a thick one of the same material.

This rule, however, must be accepted with great limitations. The puncture voltage is very largely determined by the state of the surface of the dielectric. Nevertheless, the above statement holds good approximately for a large number of solid and liquid, and gaseous dielectrics.

A very extensive set of experiments on dielectric strength has been described by Mr. T. Gray.[27] He used alternating electromotive forces of simple sinoidal form, and a frequency of 133 periods per second. The discharges were taken between the curved surfaces of two polished discs of copper, which were portions of spheres 70 cms. in diameter, all edges being rounded. He tested the dielectric strength of air, various oils, and solid dielectrics, and states the results in *kilovolts per centimetre.*

His experiments support the experience that, generally speaking, the *apparent dielectric strength* of a thin layer of a dielectric is greater than that of a thicker one.

Gray found that rupture voltage of a sheet of dielectric under an alternating electromotive force of simple sine form is identical with that due to a steady electromotive force having the same value as the maximum of the alternating force. Hence, in stating the dielectric strength in kilovolts per centimetre, the values given below are those corresponding to *the maximum value* of the alternating electromotive force employed, this maximum being calculated from the root-mean-square (R.M.S.) value observed on the voltmeter at the moment of rupture.

In the case of the alternating electromotive force used by him, this maximum value was equal to the R.M.S. value multiplied by 1·312. His results for air confirm those of previous observers. Lord Kelvin established long ago the fact that the electric force required to produce a very short spark in air between slightly rounded metallic

[26] See *The Electrician*, 1901, vol. 47, p. 758; or *Science Abstracts*, vol. iv. p. 1064.

[27] See *Physical Review*, vol. vii. p. 199.

surfaces was greater than that required to produce a longer one.[28] Mr. Gray's results for the dielectric strength of air are as follows :—

Air at Normal Pressure and Temperature.

Thickness of layer of air in centimetres.	Dielectric strength in kilovolts per centimetre.
0·02	57·5
0·04	52·5
0·06	49·5
0·08	46·2
0·10	43·6
0·20	37·8
0·40	34·5
0·60	32·7
0·80	31·1
1·0	29·8
1·20	28·8
1·40	28·8
1·60	27·4

Hence to produce a spark 1 cm. in length in air requires about 30,000 volts.

The apparent dielectric strength of air decreases, therefore, slightly with increasing thickness, and, according to Mr. Gray, ultimately it reaches some value not far from 24 kilovolts per centimetre, or 80 C.G.S. units of electric force in electrostatic measure. On this matter, however, the reader is referred to some remarks on a later page (p. 164) concerning the true dielectric strength of air.

Similar results were obtained by Gray in the case of glass. Employing a variety of glass called *crystal glass*, used for lantern slides, he found the dielectric strength for various thicknesses to be as follows :—

Crystal Glass.

Thickness in centimetres.	Dielectric strength in kilovolts per centimetre.
0·1	285
0·2	253
0·3	224
0·4	200
0·5	183
0·6	168

For window glass 0·2 cm. thick, he found the dielectric strength to be 160 kilovolts per centimetre.

He also made tests with sheet ebonite, indiarubber, mica, and micanite, with results as follows :—

Ebonite.

Thickness in centimetres.	Dielectric strength in kilovolts per centimetre.
0·093	538
0·186	434

Indiarubber Sheets.

0·135	476
0·270	318

[28] See Lord Kelvin, "Reprint of Papers on Electrostatics and Magnetism," p. 258, or *Proc. Roy. Soc.*, vol. x. p. 326, February 23, April 12, 1860, "Measurement of the electromotive force required to produce a spark in air between parallel metal plates at different distances."

Mica.

Thickness in centimetres.	Dielectric strength in kilovolts per centimetre.
0·001	2000
0·010	1150
0·02	950
0·05	750
0·10	610

Micanite.

0·05 } 0·10 }	400

Paper of various kinds impregnated with paraffin wax possessed dielectric strengths as follows :—

Material.	Thickness in centimetres.	Dielectric strength in kilovolts per centimetre.
Thin printers' paper	0·012	400
Tissue paper	0·009	510
Manilla paper	0·018	430
American linen paper	0·013	640
Typewriter linen paper	0·014	540

Fuller board, a kind of vulcanized fibre, showed a dielectric strength of 205, 192, and 169 kilovolts per centimetre of thickness of 0·005, 0·1, and 0·2 cm.

Oils of various kinds were tested in layers having thickness from 4 to 8 mm., and the following values for the dielectric strength were found, though somewhat variable.

Oils.

	Dielectric strength in kilovolts per centimetre.
Light mineral lubricating oil	48
Sperm oil	52
Vaseline oil	60
Cotton-seed oil	67
Olive oil	70
Linseed (raw) oil	83
,, (boiled) oil	85

Other observations by the same author seemed to show a decrease in dielectric strength with thickness in the case of oils. Thus, for instance, he found for vaseline oil the following values of the dielectric strength.

Vaseline Oil.

Thickness.	Dielectric strength in kilovolts per centimetre.
8 mm.	91
1 ,,	131

Paraffin Oil.

Sp. gr. 0·28. Varied between 64 and 101 kilovolts per centimetre.

Experiments by other observers substantially confirm the above results. T. W. Edmondson has measured the dielectric strength of air, and finds that his observations agree fairly well with the formula—

$$V^2 = at + bt^2$$

where t is the spark length or thickness in millimetres of the layer of air ruptured, and V is the spark potential in (C.G.S.) electrostatic units, whilst a and b are constants varying with the diameter of the spark balls as follows[29] :—

Diameter of spark balls.	a	b
0·5 cm.	235·13	82·25
1·0 „	186·35	99·42
2·0 „	144·41	114·49
3·0 „	49·41	144·71

If we reckon the spark length in centimetres and spark potential in kilovolts, Edmondson's formula reduces to the following form:—

$$\textit{Apparent dielectric strength of air in kilovolts per centimetre} = 3\sqrt{b + \frac{a}{10t}}$$

where t is the thickness in centimetres. This gives a dielectric strength of 33 $\frac{\text{kv.}}{\text{cm.}}$ for 1 cm. thick, which agrees fairly well with observations by Baur, Gray, and others, and it shows that the apparent dielectric strength decreases with increasing thickness, and finally reaches a limit $3\sqrt{b}$. The formula, however, must not be extrapolated beyond the limits of observations.

Edmondson also gives a series of useful curves for the dielectric strength of various oils, all of which show a slight increase of dielectric strength with decrease of thickness of film punctured.

When using as discharge surfaces brass balls 2·6 cms. in diameter and within the limits 2 to 10 mm. for sparking distance, a simple linear formula for the spark potential can be conveniently employed, viz.—

$$V = 10{\cdot}2t + 7{\cdot}07$$

where V is the spark potential in electrostatic (C.G.S.) units and t is the spark length in millimetres in air at normal pressure and temperature.[30] This is transformed into measurement in volts by multiplication by 300.

Hence—

$$\textit{Spark voltage in air at normal pressure} = 2121 + (3060 \times \textit{spark length in millimetres})$$

$$\text{or} \quad \left.\begin{matrix}\textit{Apparent dielectric strength of}\\ \textit{air in kilovolts per centimetre}\end{matrix}\right\} = 30{\cdot}6 + \frac{21}{\textit{spark length in millimetres}}$$

M. O'Gorman has given values for the dielectric strength of certain insulating materials used in cable manufacture as follows[31] :—

[29] See *Physical Review*, 1898, vol. vi. p. 65.

[30] The above formula embodies results obtained in the physical laboratory of University College, London.

[31] See *Journal of the Institution of Electrical Engineers*, vol. 30, p. 680, Appendix VIII., M. O'Gorman, "Insulation on Cables."

Material.	Dielectric strength in kilovolts per centimetre.
Gutta percha	109
Paraffin wax (solid)	130 to 270
,, (melted)	56
Vaseline	91
Resin oil	270 to 1350

There are so many circumstances which cause variation in the dielectric strength of insulators that the figures given by different observers are not in very close agreement. C. Baur has given the results of some measurements on various dielectrics as follows [32] :—

Dielectric.	Dielectric strength in kilovolts per centimetre.	
Dry air	33	
Vulcanized indiarubber	100	
Mica	580	
Empire cloth	125	These are various fibrous materials impregnated with oils or resins.
Fuller board	190	
Impregnated jute	220	

The practical conclusion to be drawn from the above-described experiments is that in air at ordinary pressure and temperature, and for metallic spark balls a few centimetres in diameter, electric sparks pass and rupture the air when the electric force in the gap between the balls varies from 4500 to 3000 volts per millimetres of spark length, as the spark length increases from 1 mm. in length and upwards.

To create a spark in air of 1 cm. in length between such surfaces requires a steady voltage of about 30,000 volts, or an alternating voltage of sinoidal form having an effective or R.M.S. value of nearly 21,000 volts, and at the same rate for greater spark lengths.

The whole subject of the dielectric strength of air has recently been rediscussed by Dr. A. Russell (see *Proc. Phys. Soc. Lond.*, November, 1905) in a valuable paper. He points out that the results of various observations with different-sized discharge balls differ considerably. It is a well-known fact, as first shown by C. F. Varley in 1871 (*Proc. Roy. Soc.*, January 12, 1871), that there is a minimum sparking potential in air and other gases below which it is impossible to obtain a discharge. For air at normal pressure and temperature this is not far from 790 volts (see the Hon. R. J. Strutt, "On the Least Potential Difference required to produce Discharge through Various Gases," *Phil. Trans. Roy. Soc. Lond.*, 1899–1900, vol. 193A, p. 377). Hence, if there is a potential difference, V kilovolts, between two metal balls, we may say that the effective potential difference is in fact $(V - 0{\cdot}79)$ kilovolts. Kirchhoff published, in 1860, a valuable paper in *Crelle's Journal*, entitled, "Über die Vertheilung der Elektricität auf Zwei leitenden Kugeln," in which he shows how to express the maximum electric force in the form of an infinite series. Dr. Russell has provided a simple proof of Kirchhoff's formula by the method of electric images.

When the discharge balls are of equal size and at equal and

[32] See *The Electrician*, 1901, vol. 47, p. 758, or *Science Abstracts*, vol. iv. p. 1067.

opposite potentials, $+\frac{V}{2}$ and $-\frac{V}{2}$, the shortest distance between them being x, Dr. Russell shows that the maximum electric force is expressed by $\frac{Vf}{x}$, where V is the potential difference of the balls, and f is a function of their diameter $2a$ and distance x. He gives the following values of f for various values of $\frac{x}{a}$:—

$\frac{x}{a}$	f	$\frac{x}{a}$	f
0·0	1·000	1·5	1·559
0·1	1·034	2·0	1·770
0·2	1·068	3·0	2·215
0·3	1·103	4·0	2·678
0·4	1·138	5·0	3·151
0·5	1·174	6·0	3·631
0·6	1·209	7·0	4·117
0·7	1·246	8·0	4·601
0·8	1·283	9·0	5·095
0·9	1·321	10·0	5·586
1·0	1·359	100·0	50·51
		1000·0	500·50

If, then, V is measured in kilovolts, the true dielectric strength of air is given by the maximum value of the electric force, viz. R_{max}; and

$$R_{max} = \frac{(V - 0·79)}{x} f \quad . \quad . \quad . \quad . \quad . \quad . \quad (79)$$

The fraction 0·79 is the value in kilovolts of the potential difference, which must be exceeded before any spark begins, and the quantity f in the above expression (tabulated above) is a factor by which the average effective kilovolts per centimetre must be multiplied to give the maximum electric force. From a discussion of various results by different experimentalists, Dr. Russell shows that for air at normal pressure and temperature *the true dielectric strength* lies between 38 and 39 kilovolts per centimetre, or in electrostatic units to a force of 127. The true dielectric strength of air is therefore expressed by a number about one-third larger than the average kilovolts per centimetre for sparks 1 cm. in length taken between balls 1 or 2 cms. in diameter.

In the construction of high-tension condensers a liberal margin should be allowed as a *factor of safety*, and the working pressure should not be more than a quarter of the rupture voltage.

Thus, in the case of glass, Gray's experiments show that for a thickness of 2 to 3 mm. the dielectric strength is from 253 to 224 kilovolts per centimetre. This means that a voltage of 62,000 volts will pierce a plate of glass 2 mm. thick. If we construct a condenser of glass plates 0·1 inch or 2·5 mm. thick, the safe working voltage would be about one-third of the above breaking voltage, viz. 20,000 volts, equivalent to a 6 or 7 mm. spark in air.

The above is in accordance with practical experience. Ebonite and mica or micanite have undoubtedly greater dielectric strength

than glass. Ebonite is about twice, and mica is about three times, as strong; whilst micanite, which consists of plates of mica stuck together with shellac, has a still greater dielectric strength.

Many circumstances, however, contribute to affect the dielectric strength. J. Kiessling and B. Walter have called attention to the fact that if a tube of dielectric is partly immersed in oil and electric stress applied to the material it punctures at the surface of the oil.[33] In the same way, if a drop of melted paraffin wax is placed on a sheet of glass, and this is afterwards submitted to electric strain between electrodes the puncture takes place at the edges of the wax. If, however, a needle prick is made in the wax, puncture will more readily occur through this hole. Plates of ebonite coated with tinfoil on both sides and placed in oil for use as high-tension condensers are generally found to puncture near the edges of the tinfoil if an excessive voltage is used. The electric force has the highest value at the edges of the metal plates, and the puncturing is determined, not by the mean but by the maximum electric force acting on the dielectric.

Thus a sheet of ebonite 4·2 mm. thick withstood a voltage equal to a 50-cm. spark in air. This is equivalent to a dielectric strength of 3000 kilovolts per centimetre. If, however, a drop of wax was placed on the surface, the ebonite gave way under a stress of about half the above value. If a needle hole was made in the wax the ebonite was pierced at that spot by a force of 600 kilovolts per centimetre.

Hence the authors conclude that any scratches or flaws on the surface of a sheet of dielectric greatly reduce its strength. They state that bubbles in glass, as long as they do not open upon the surface, do not bestow particular weakness at that point. These experiments show that in the case of sheets of dielectric to be used for making high-tension condensers it is important to avoid the slightest pricking or cracking of the surface.

In the case of gases, pressure exercises a most marked effect on their dielectric strength.

Wolf has given a formula for the electric force in electrostatic units required to bring a discharge in air under a pressure of P atmospheres between metal balls 10 cms. in diameter.[34] If E is this electric force, then—

$$E = 107P + 39 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (80)$$

Thus if $P = 1$, then $E = 146$ E.S. units, or $146 \times 300 = 43{,}800$ volts per centimetre. Accordingly the dielectric strength at normal pressure, according to Wolf, is 43·8 kilovolts per centimetre, which is higher than the value obtained by other observers.

The above formula holds good up to 5 atmospheres. Hence, if $P = 5$, then $E = 574$, and this corresponds to a dielectric strength of 172·2 kilovolts per centimetre. The dielectric strength is thus nearly proportional to the pressure, and the potential difference required to produce a spark between rounded metallic surfaces varies almost as the distance between them and as the pressure, *i.e.* upon the mass of gas lying between the electrodes.

[33] *Ann. der Physik*, June 4, 1903, vol. 11, p. 570, or *Science Abstracts*, vol. vii. A., p. 603.

[34] *Wied. Ann.*, 37, 1889, p. 306.

In forming oscillating circuits by joining in series a spark gap, condenser, and inductance, it is always prudent to consider what spark length is permissible, having regard to the thickness and nature of the dielectric used. Few glass Leyden jars will bear more than 20,000 volts without risk of puncture. Hence this corresponds to a spark length of 7 or 8 mm. in air. If, then, glass-plate condensers or Leyden jars are used and larger spark gaps are required, the jars must be placed in series in sufficient number to bear the strain. Thus, if the capacity of a single jar is required, but a spark length

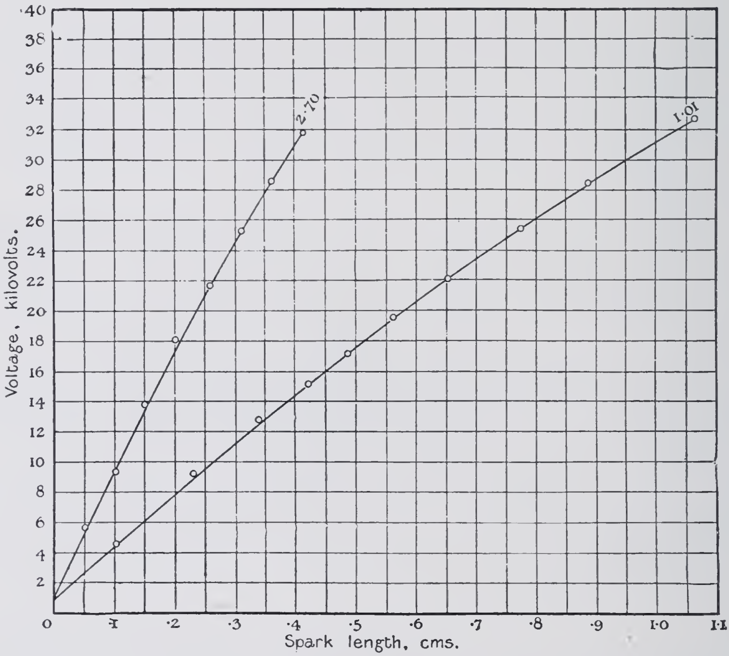


FIG. 19.—Spark Voltages for 2·54 cms. Spark Balls with Alternating Voltage.

of 1·5 cm., four jars should be arranged, two in parallel and two in series, and so on.

A very useful series of experiments have been carried out by Mr. E. A. Watson on the dielectric strength of compressed air.[35] He employed spark balls of various sizes and various spark lengths, and measured the spark voltages in dry air of various pressures with alternating and also with direct currents. The two curves in Fig. 19 show the variation of spark voltage (alternating) with spark length for spark balls 2·54 cm. (= 1 inch) in diameter in air under 1·01 atmosphere or normal pressure, and air at 2·7 atmospheres pressure. It will be seen that the spark voltage is more than doubled.

In Fig. 20 are shown curves for the same sized balls taken with alternating voltages and for pressures from 3·25 to 7·36 atmospheres.

[35] *Journal of the Institution of Electrical Engineers*, vol. 43, p. 113, 1909.

The lines in Fig. 21 show the spark voltages for various spark lengths with the same sized balls but with direct current.

His results show that the dielectric strength in kilovolts per cm. varies almost proportionally to the pressure, and more precisely may be expressed by the formula—

Dielectric strength = 20 + 25·6 times pressure in atmospheres (81)

Thus for 10 atmospheres it is 276.

The dielectric strength of various oils is an important practical matter. In investigations on high frequency currents the type of

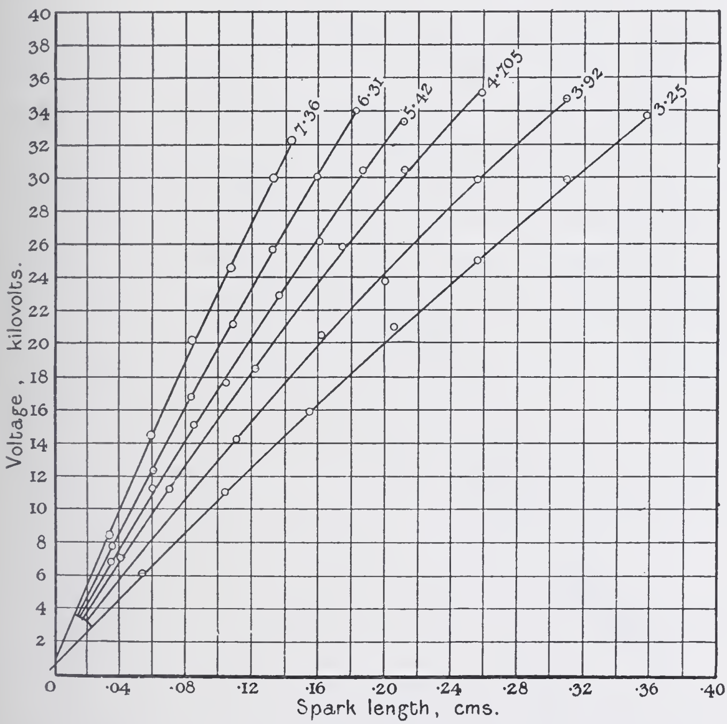


FIG. 20.—Spark Voltages for 2·54 cms. Spark Balls with Alternating Voltage.

condenser most convenient for the purpose consists of metal plates placed in oil, the oil forming the dielectric, and in practical radio-telegraphy when the dielectric used is glass, the glass plates having metal plates applied to both surfaces, the whole arrangement has to be immersed in oil to prevent glow discharges, or sparking over the glass margin.

Since oils differ very much in dielectric strength, and as this quality is greatly dependent on temperature, and on the presence of moisture in the oil, oils to be used for this purpose should be carefully tested for dielectric strength. This is done in the following manner. The oil to be tested should be warmed up to 70° Fahr., and placed in a perfectly dry glass beaker. A bar of ebonite which can

rest across the vessel carries two rods to which metal balls 1 centimetre in diameter are attached. These balls being so set that their nearest surfaces are 2 mm. from each other. The balls must be well below the surface of the oil. The balls are then connected to a high tension electrostatic voltmeter suitable for measuring voltages up to 30,000 or 40,000 volts, and are also connected to the secondary terminals of a transformer which can give these voltages when fed with alternating current of simple sine form on its primary side. The secondary voltage is best regulated by inserting a variable rheostat or choker in the primary circuit. The voltage is then slowly

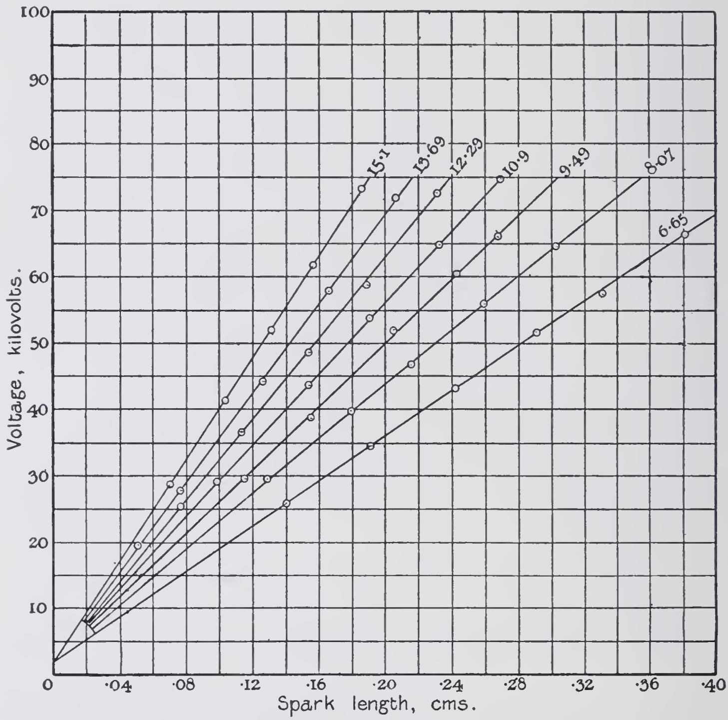


FIG. 21.—Spark Voltages for 2·54 cms. Spark Balls with Direct Current.

raised until a spark passes through the oil, when the voltmeter must be read. It is not well to employ points as spark surfaces, because the breakdown voltage is greatly affected by the sharpness of these points, and it is not easy to define this sharpness so as to make the conditions of the experiment definite. On the other hand, with small spheres as spark surfaces the electric field is definite and predeterminable in all cases.

7. The Practical Measurement of the Capacity of Conductors.—If there be any two conductors, and these are respectively charged with equal quantities of electricity of opposite sign, and if a difference of potential having a value of one unit is created between them, then

the quantity of electricity or the charge on either of the conductors is a measure of their *capacity* with respect to each other. If any body is charged to unit potential with respect to the earth, and all other conductors are removed to a very great distance, the charge on the conductor in question is a measure of its *capacity with respect to the earth.* The quantity of electricity which will raise the body to unit potential above the earth depends on its form and position and upon a quality of the surrounding insulator called its *dielectric constant.* We may define the dielectric constant as follows :—

If electric force acts upon a dielectric it produces in it electric displacement. If a uniform electric force acts upon a dielectric and produces in it uniform electric strain or displacement, the numerical ratio of the displacement through unit area to the force, or of the electric strain to the electric stress, is called the *dielectric constant* of this insulator. The name is not well chosen, because the so-called constant is far from being constant, but varies with temperature, voltage, and frequency, and it would be better to coin another name.[36] The dielectric constant bears the same relation to electric strain and stress or electric force and displacement that magnetic susceptibility bears to magnetic force and magnetization. The dielectric constant may otherwise be defined as the number which expresses the ratio in which the capacity of any air condenser is increased if the air is wholly replaced by the dielectric in question.

If C is the capacity of any air condenser when its plates are charged to a potential difference, V, then if Q represents the quantity of electricity stored in the condenser, we have—

$$Q = CV$$

Hence $C = \frac{Q}{V}$, and we may define the capacity of a conductor as the ratio of its charge to its potential. If the air is wholly replaced by some other insulator and the capacity becomes K times C, or KC, then K is the dielectric constant of the insulator.

The process of determining the dielectric constant generally consists in measuring the capacity of some form of air condenser and then measuring it again when for air we have substituted the insulator in question.

It was in this manner, and by the increase in capacity so observed, that Faraday made the first measurements of dielectric constant.[37]

It is not necessary here to consider all the numerous methods for determining dielectric constants which have been proposed, nor the whole of the processes by which electric capacity can be determined. These are explained in text-books on physics and electrical measurement.

It is, however, desirable to explain rather fully one method of measuring small capacities at low or moderate frequencies, which the author, in conjunction with Prof. W. C. Clinton, has perfected, as it

[36] The term *permittance* has been employed by Mr. Oliver Heaviside to signify that which is generally called capacity, and the word *permittivity* to denote the same quality which the terms dielectric constant, or specific inductive capacity, are generally used to express.

[37] See Faraday's "Experimental Researches in Electricity and Magnetism," vol. i. ser. xi. § 1187.

affords a means of making many of the capacity measurements which are required in connection with high frequency electric current investigation or Hertzian wave telegraphy.

If we charge an insulated conductor to a potential V, and measure the charge Q so given, then the ratio $\frac{Q}{V}$, when Q and V are measured in consistent units, gives us the capacity of the conductor.

If that capacity is small, we may repeat the charging n times a second and measure the quantity nQ. Suppose, then, we discharge this quantity nQ in one second through a galvanometer. It is equivalent to a current nQ in its effect on the instrument. Hence, if we have the means to continue this process uniformly, and can calibrate the galvanometer, we have all the information necessary for measuring the capacity.

Many methods have been suggested for conducting the above operation, but there are practical difficulties in it which have only been overcome by the invention of a thoroughly effective rotating commutator, designed to effect this process of charging a conductor with a known potential, then sending the charge through a galvanometer, and repeating the process uniformly a known number of times per second.[38]

The details of this commutator are shown in Fig. 22.

The instrument consists of a continuous current electric motor of $\frac{1}{6}$ h.p., but for certain purposes, and where very small capacities have to be measured, it is preferable to employ a motor of $\frac{1}{2}$ h.p. This motor (not shown in the diagram) is bolted down upon a baseboard, and has connected with it a starting and regulating resistance. The motor is preferably 100 or 200 volt shunt-wound motor. To the shaft of this motor is connected by a flexible coupling the commutating arrangement (shown in the diagram in Fig. 22), the function of which is to charge the capacity or condenser to a given voltage, and then discharge it through a galvanometer, repeating this process four times in each revolution of the motor. This commutator is fixed on a shaft, carried in well-lubricated bearings, supported on two small A frames, P (see Fig. 22). On this shaft are held, by means of ebonite brushes and washers, three gunmetal discs or wheels, of which the centre one, I, is in shape like an eight-rayed star, whilst the two outer ones, A and B, are like crown wheels, each having four teeth. The three wheels are so set on the shaft that the teeth or projections of each of the two outer wheels interlock or fall in the space between the teeth of the other, whilst the radial teeth of the intermediate wheel occupy the intervals between the teeth of the two outer wheels. The developed surface of this triple wheel is shown in Fig. 23. The whole outer surface is turned true, and forms a barrel about 4 inches in diameter and $2\frac{1}{2}$ inches wide. On this barrel rest three brass gauze brushes, b, which are carried in well-insulated brush-holders, R, and by means of three springs and levers, L, the brushes are firmly pressed against the barrel, the two outer brushes resting on the continuous portions or flanges of the two outer wheels

[38] See J. A. Fleming and W. C. Clinton, "On the Measurement of Small Capacities and Inductances," *Proc. Phys. Soc. Lond.*, 1903, vol. 18, p. 386; also *Phil. Mag.*, May, 1903, vol. v. ser. 6, p. 493.

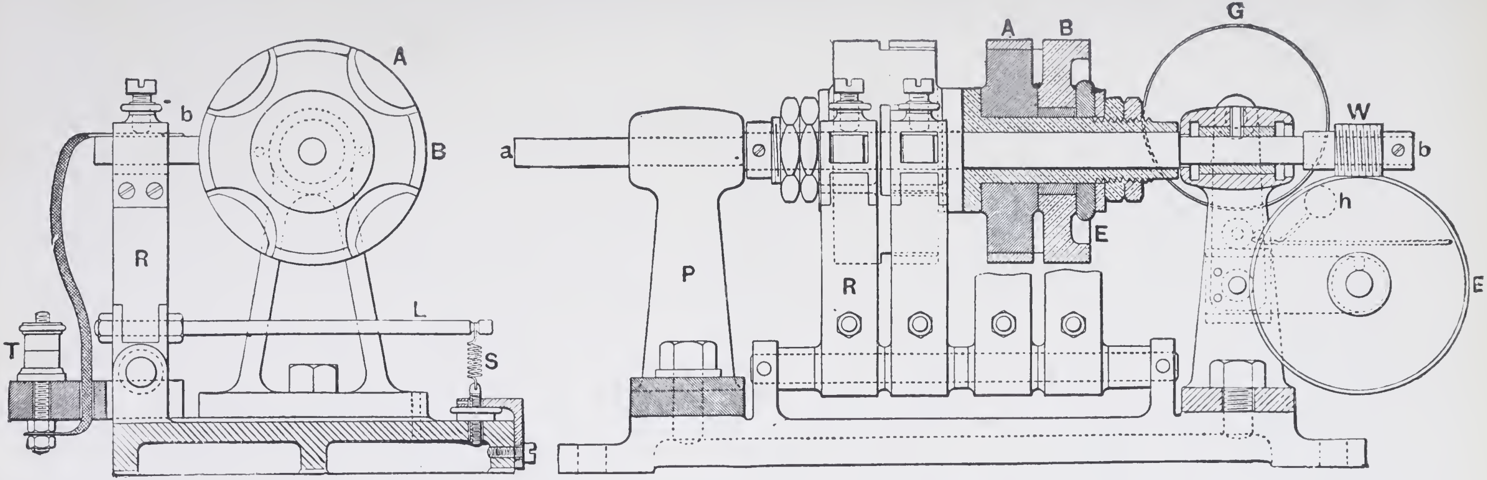


FIG. 22.—Fleming and Clinton Revolving Commutator for the Determination of Small Capacities.

and B, and the middle brush occupies the centre line and makes contact either with the wheel A or wheel B, or with the intermediate wheel I, according to their position. It will be seen, then, that as the commutator runs round, the middle brush is alternately brought into metallic connection with first one and then the other of the two brushes on either side. The function of the middle wheel, I, is to afford a stepping-piece to prevent any shock or jar as the middle brush passes over from one connection to the other. It also prevents the middle brush from short-circuiting the two outer brushes at any time. If, then, one terminal of the galvanometer is connected to the brush pressing against the wheel A, and one terminal of a battery is connected to the brush pressing against wheel B, and one terminal of a condenser is connected to the middle brush, the other terminals of the battery, galvanometer, and condenser being connected together, it will easily be seen that as the commutator rotates, the condenser is first charged at the battery, and then discharged through the galvanometer. It is convenient to employ a speed of 1200 and 1700 revolutions per minute. To count the rotations of the commutator, a worm, W, on the shaft drives a wheel, G, of such gear that the

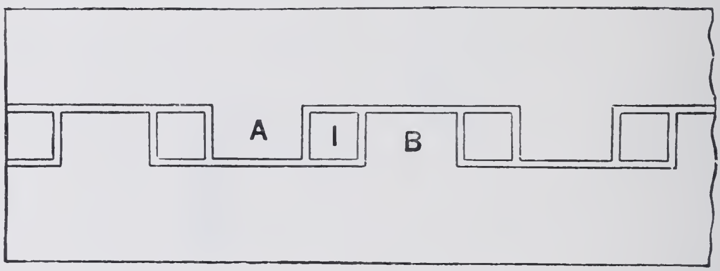


Fig. 23.

latter makes one revolution for every hundred revolutions of the commutator. This wheel carries a pin, which at each revolution causes a hammer, h, to strike a gong, E. Every hundred revolutions, therefore, of the motor or commutator the gong gives one stroke, and by means of a stop-watch it is easy to take the time of ten strokes of the gong—in other words, to ascertain the time in seconds of a thousand revolutions of the motor, and therefore of the number of commutations per second. In the case of the motor described, 1000 revolutions take place generally in 40 seconds, which is at the rate of 1500 per minute, and therefore corresponds with 100 commutations of the condenser per second.

Various methods of making the rubbing contacts have been used, and brass gauze brushes found to be the best. Carbon brushes were tried at one time, but were not so good as the brass gauze. It is essential that the commutator surface should be kept bright and clean, and the brass gauze brushes do this themselves when adjusted to the right pressure.

Associated with this commutator, it is best to make use of a galvanometer of the movable coil type. By the aid of this instrument, given a source of constant voltage by which the motor can be

driven steadily, such as a secondary battery, the measurement of small capacities becomes an exceedingly easy matter.

In the case of most movable coil galvanometers the scale deflections are by no means proportional to the current, and hence when measuring a series of capacities it is desirable afterwards to plot a calibration curve of the galvanometer scale, from which the condenser currents can be read off directly in microamperes. This, however, is always easily accomplished. In addition, we have to measure the potential of the discharging battery. For most practical purposes this can be done by a Weston voltmeter.

Then let V represent the voltage of the battery charging the condenser or aerial, C the capacity of the condenser in microfarads, A the current in microamperes through the galvanometer, and n the number of charges per second, then—

$$A = nCV$$

$$\text{or} \quad C = \frac{A}{nV}$$

To determine the numerical value of the capacity, we have, therefore, to standardize the galvanometer or determine the ampere value of the steady current which will make the same deflection. This can be accomplished by shunting the galvanometer with a known small resistance, placing the two shunted galvanometers in series with another high resistance, and then applying to the terminals of this circuit a cell of known electromotive force. If a megohm resistance is available it is generally possible, by placing this in series with the galvanometer, to standardize the galvanometer off the same battery used to charge the condenser. In this case no voltage measurement is necessary.

To avoid the necessity for standardizing the galvanometer and measuring the voltage of the charging battery, the author has devised a method employing a differential galvanometer which in principle is as follows: The condenser discharges, as above described, pass through one coil of the differential galvanometer, the other coil being traversed by a steady current taken from the same battery and therefore having the same voltage. This second coil is shunted by means of a shunt S, and has in series with it a high resistance, r. If, then, these resistances are arranged so that the galvanometer shows no deflection, we have the following equation for the capacity:—

$$\frac{nVC}{10^6} = \frac{V}{r + \frac{GS}{G+S}} \times \frac{S}{G+S}$$

$$\text{Hence} \quad C = \frac{S10^6}{nr(G+S) + nGS} \quad . \quad . \quad . \quad . \quad . \quad (82)$$

where G is the resistance of the galvanometer and S that of the shunt, and n the number of charges per second sent through the galvanometer.

This determines the capacity in terms of a conductance and the reciprocal of a time, thus reducing the number of dimensional quantities to be measured to the minimum.

In carrying out this method, it is perfectly impossible to use an

ordinary movable needle differential galvanometer, because with an electromotive force of 100 volts or more between the wires forming the coils a leakage occurs between them which entirely vitiates the indications. A special form of differential movable coil galvanometer is therefore necessary. In this galvanometer there are two sets of fixed field-magnets, and also two movable galvanometer coils, completely insulated from one another, but attached to the same stem, which also carries the mirror. Very fine spiral flexible wires convey the currents into and out of each coil. In order to make the galvanometer differential, and therefore yield no deflection when the same current is passed in opposite directions through the coils, it is necessary to be able to adjust exactly the field strength in the air-gap of the fixed magnets. This we accomplished by means of two curved pieces of soft iron, P, which are moved by screws to or from the field-magnets, N, S, so as to shunt more or less of the lines of flux, which pass between the pole-pieces of the magnet. In this manner we find we can construct a movable coil differential galvanometer which shows no deflection when the same or equal currents are passed in opposite directions through the two coils, yet each coil is perfectly insulated from the other.

Employing such a differential movable coil galvanometer in connection with a commutator, we get rid of all necessity for measuring any voltage or electromotive force, and reduce the measurement of capacity simply to a determination of the speed of the commutator (which can be taken with great accuracy by means of a stop-watch) and the known value of the shunt and series resistances in connection with one coil of the galvanometer. Moreover, we can always tell from the speed of the commutator exactly the time during which the condenser is in connection with the galvanometer, and hence whether the time of contact is, as it should be, large compared with the time-constant of the discharge circuit.

By the aid of the above-described apparatus the measurement of very small capacities becomes as simple as the measurement of small resistances.

Measurements must always be made by difference, and account taken of the capacity of the commutator itself and of the connecting leads. Thus, for instance, if the capacity of a Leyden jar has to be measured, the jar is connected as shown in Fig. 24, the outer surface to the common terminal of the battery and galvanometer, and the inner one to the middle brush of the commutator. The commutator is then run up to speed, and the speed measured by taking the time with a stop-watch of 1000 revolutions or ten bell strokes. If the galvanometer deflection remains steady, this shows the speed is uniform. When the deflection has been measured the jar is removed, and the leads open circuited. Another run is then taken, and the galvanometer deflection measured. The value of the current A to be inserted in the formula $C = \frac{A}{nV}$ is the difference of the currents in microamperes corresponding to these two deflections.

If the capacity being measured is that of an insulated body, such as an aerial wire or other object, then it is connected to the middle brush of the commutator, and the common terminal of the battery

and galvanometer must be "earthed." The same procedure as above described must be followed to eliminate the capacity of the commutator and leads.

To employ the instrument for the measurement of dielectric constants, some form of air condenser must be provided in which the dielectric can be substituted for air and the capacity then measured. There are not many forms of condenser which can be used for this purpose.

If two insulated metal plates of area S square centimetres are set up in air parallel to each other at a distance d centimetres, we have an air condenser which has a certain capacity. Between the central portion of the plates the lines of electrostatic force spring straight across normally to the plates, and as far as this part of the capacity is

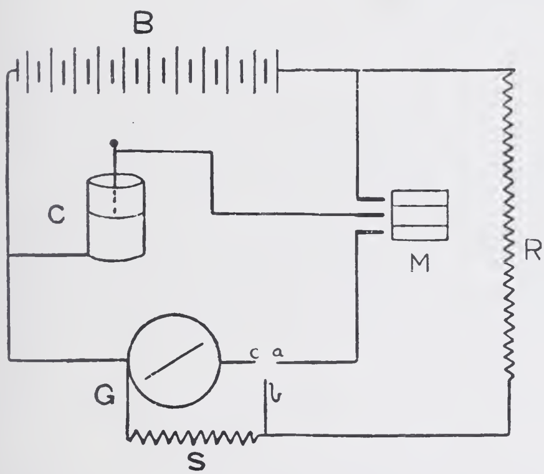


FIG. 24.—B, battery; C, condenser; G, galvanometer; M, commutator; R, standardizing resistance; S, shunt; a, b, c, three-way plug switch.

concerned it can be calculated in electrostatic units by the formula usually given in the text-books, viz.:—

$$C = \frac{A}{4\pi d} \text{ (in electrostatic units)}$$

where A is some area of the plates less than that of their actual area S. The whole capacity cannot, however, be calculated by the simple rule. There is, in addition, a distribution of electric force at the edges, and beyond the edges of the plates in curved lines, and if the distance of the plates is large compared with their diameter, the capacity due to this part of the flux may amount to a large fraction of the total of the whole. Hence the above simple formula is far from giving the true capacity of a pair of parallel plates. In the same manner, the substitution of a sheet of dielectric of thickness d for the air between the plates will not enable us to calculate exactly the dielectric constant. For such a sheet only occupies part of the space filled with lines of electrostatic force.

Kirchhoff has given [39] a formula for calculating exactly the capacity of a pair of parallel circular plates, each of radius r, placed at a distance d apart in the air, as follows:—

$$C = \frac{\pi r^2}{4\pi d} + \frac{r}{4\pi d}\left\{d \log_\epsilon \frac{16\pi r(d+t)}{\epsilon d^2} + t \log_\epsilon \frac{d+t}{t}\right\} + C' \quad (83)$$

where t is the thickness of the plates, C' is any part of the capacity which does not change with the distance d, and ϵ is the base of Napierian logarithms. Suppose, then, that we place between the plates a circular disc of any dielectric having a dielectric constant K, such disc being smaller than the plates, and having a radius r_1 and a thickness d_1. Let the plates be moved up to touch this disc, placed concentrically between them. Then the capacity of the system is given by the formula—

$$C_1 = \frac{K\pi r_1^2}{4\pi d_1} + \frac{\pi r^2 - \pi r_1^2}{4\pi d}\left\{d_1 \log_\epsilon \frac{16\pi r(d_1+t)}{\epsilon d_1^2} + t \log_\epsilon \frac{d+t}{t}\right\} + C' \quad (84)$$

Hence by measurement of C_1 and the dimensions we can find K.

The assumption made is that the disc of dielectric does not disturb the distribution of the field outside itself, but only intensifies the field within itself in the ratio of K : 1. This assumption is not quite legitimate, but the method is approximately correct, and certainly far less incorrect than the assumption usually made, that the whole original capacity of the plates is merely increased in the ratio of K : 1 by inserting a plate of dielectric of the same size as the plates between them. The above method, using Kirchhoff's formula, was employed by Messrs. Pollock and Vonwiller in a measurement of the dielectric constant of plate glass.[40]

If we put $t = 0$ in Kirchhoff expression, we have the capacity of two infinitely thin circular discs at a distance d apart. It reduces them to—

$$C = \frac{\pi r^2}{4\pi d} + \frac{r}{4\pi} \log_\epsilon \frac{16\pi r}{\epsilon d}$$

$$\text{or} \quad C = \frac{\pi r^2}{4\pi d}\left(1 + \frac{d}{\pi r} \log_\epsilon \frac{16\pi r}{\epsilon d}\right)$$

The second term in the bracket, therefore, represents that fraction by which the capacity of the real condenser exceeds that of the ideal or text-book condenser, in which the electric force is considered simply to pass normally from plate to plate. If the plates are 10 cms. in radius and 1 mm. apart, then $\frac{r}{d} = 100$, and $\frac{d}{\pi r} \log_\epsilon \frac{16\pi r}{\epsilon d}$ is nearly $\frac{1}{40}$, so that the real capacity exceeds the capacity calculated from the formula $\frac{\pi r^2}{4\pi d}$ by only $2\frac{1}{2}$ per cent.

We are led, therefore, to this conclusion, that if the circular condenser plates are very large compared with their distances apart,

[39] G. Kirchhoff, *Gesammelte Abhandlungen*, p. 112, "Zur Theorie des Condensators." See equation (18).

[40] See Pollock and Vonwiller, "Some Experiments on Electric Waves in Short Wire Systems and on the Specific Inductive Capacity of a Specimen of Glass," *Phil. Mag.*, 1902, vol. 3, ser. 6, p. 586.

we may calculate the capacity of the condenser by the simple formula—

$$C = \frac{S}{4\pi d \times 9 \times 10^5} \text{ microfarads} \quad . \quad . \quad . \quad . \quad (85)$$

where S is the area of one plate in square centimetres, and d is their distance apart in centimetres, $\frac{d}{S}$ being very small.

On the other hand, to abolish the irregular edge distribution, we may make use of a *guard plate*. One of the condenser plates has in it a large aperture which is nearly filled by another insulated smaller plate. The two last plates are fixed in the same plane.

The outer margin of the smaller plate is called the guard plate. When the small plate and its guard plate are charged to one common potential, differing from the potential of the opposed larger plate, the lines of electrostatic force spring straight across between the two plates, and the capacity of the small plate with respect to the opposed one is very nearly given by formula $\frac{S}{4\pi d}$, where S is the area of the small plate and d its distance from the other. There is, however, some difficulty in applying the charge and discharge method to this arrangement, as the guard plate must be discharged at the same instant as the guarded plate, but not through the galvanometer.

In place of plates we may employ concentric cylinders. If R_1 be the inside diameter of the outer cylinder, and R_2 the outside diameter of the inner cylinder, and l the common length of both cylinders, all measured in centimetres, then the capacity in electrostatic units with air as dielectric is given by—

$$C = \frac{l}{2 \log_\epsilon \frac{R_1}{R_2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (86)$$

provided we neglect the distribution of force at the ends of the cylinders. This can only be legitimately done when their length is very great compared with the difference between R_1 and R_2.

If a substance having a dielectric of constant K is substituted for air, the capacity becomes—

$$C = \frac{Kl}{2 \log_\epsilon \frac{R_1}{R_2}} \text{ (electrostatic units)}$$

$$\text{or} \quad C = \frac{Kl}{4145400 (\log_{10} R_1 - \log_{10} R_2)} \text{ microfarads} \quad . \quad (87)$$

There is, however, a distribution of electric force in curved lines at the ends of the cylinders, which in the case of short cylinders renders the above formula inapplicable.

The only form of condenser in which this edge effect is absent is in the case of concentric spheres. If a solid sphere of metal of radius R_2 is supported concentrically with a hollow sphere of inner radius R_1, the dielectic being air, it is easy to show that the capacity in electrostatic units is given exactly by the expression—

$$C = \frac{R_1 R_2}{R_1 - R_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (88)$$

If we substitute for air any other insulator quite filling up the space between the spheres and the capacity becomes K times as great, then K is the dielectric constant of that insulator. A form of double cone condenser was designed by the author for certain experiments on the dielectric constant of liquids or frozen liquids. It consists of two coaxial cones of metal (see Fig. 25), which can be adjusted to have any desired interval between the inside of one cone and the outside of the other. An ebonite or glass peg at the bottom holds the cones coaxially. This interspace can be fitted with liquid and the capacity of the condenser so formed taken.[41]

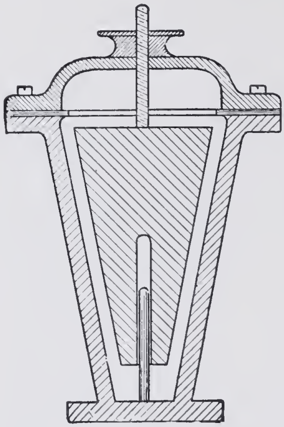


Fig. 25.—Cone Condenser.

There are several simple cases of conductors insulated in space in which the capacity can be calculated from the dimensions of the conductor. Thus if a metal sphere is hung up in infinite space, that is, all other conductors removed by a very great distance, the capacity of the sphere in electrostatic units is numerically equal to its radius in centimetres. Since 1 mfd. is equal to 900,000 electrostatic units, the capacity C of a sphere of radius R centimetres hung up in a medium of dielectric constant K, all other bodies being very far off, is given by the rule—

$$C = \frac{KR}{9 \times 10^5} \text{ (microfarads)}$$

On the other hand, we must not regard an ordinary sized room as representing infinite space electrically speaking. If a sphere 1 metre in diameter is hung up in a room 30 feet by 30 feet by 15 feet, the real capacity of the sphere would be about 10 per cent. greater than that given by the above rule.

Another useful case is that of a flat circular disc. The capacity of a disc of diameter d centimetres insulated in free space is $\frac{d}{\pi}$ electrostatic units, or $\frac{d}{\pi \,.\, 9 \,.\, 10^5}$ mfds.

A circular disc about 5 feet in diameter insulated by being hung up by a silk string in the centre of a large room has a capacity about 10 per cent. more than that given by the above formula. In measuring such very small capacities a convenient unit is the micro-microfarad (mmfds.), which is one-millionth of a microfarad. Hence a thin circular disc of which the diameter is 28·27 cms. = 9π cms. has a capacity in free space of 10 mmfds. Hung up in a large room, it would really have about 11 mmfds. capacity.

Another important case is that of a thin long circular-sectioned wire suspended in space. Such a wire may be taken to be a limiting

[41] See Fleming and Dewar on "The Dielectric Constant of Certain Frozen Electrolytes at and above the Temperature of Liquid Air," *Proc. Roy. Soc. Lond.*, 1897, vol. 61, p. 299.

form of an ellipsoid of revolution. The capacity C of an ellipsoid with semi-axes a, b, and c in infinite space is given by the expression [42]—

$$\frac{1}{C} = \frac{1}{2}\int_0^\infty \frac{du}{\sqrt{(a^2+u)(b^2+u)(c^2+u)}} \quad . \quad . \quad . \quad (89)$$

If we put $b = c$ and $\frac{b}{a}$ very small, the above integral becomes equal to—

$$C = \frac{2a}{2\log_\epsilon \frac{2a}{b}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (90)$$

If we call l the length of a wire and d its diameter, then we may say that the capacity of such a wire in free space in electrostatic units is given by—

$$C = \frac{l}{2\log_\epsilon \frac{2l}{d}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (91)$$

The capacity, therefore, of a wire l cms. long and d cms. in diameter, insulated from the earth and considerably removed from it, is—

$$C = \frac{l}{4{\cdot}6052 \log_{10}\frac{2l}{d} \times 9 \times 10^5} \text{ microfarads} \quad . \quad . \quad (92)$$

This last formula may be put in the form—

$$C = \frac{l}{4{\cdot}1454 \log_{10}\frac{2l}{d}} \text{ micro-microfarads} \quad . \quad . \quad . \quad (93)$$

and gives us a very useful formula for the approximate predetermination of the capacity of a vertical wire used as an antenna for wireless telegraphy. As an illustration of the effect of the proximity of the earth, we may, however, give the following figures:—

A circular metallic disc 60 inches in diameter was suspended and insulated in one room of the Pender Electric Laboratory of University College, a room about 40 feet by 50 feet by 18 feet. The calculated capacity by the formula $\frac{d}{\pi}$ is 53·44 mmfds., the measured capacity was found to be 59·95 mmfds., or 10 per cent. greater.

A wire was set up in the open air suspended and insulated from a mast. The length was 111 feet, and diameter 0·085 inch, or 0·215 cm. The calculated capacity from the ellipsoid formula is 181 mmfds. The observed capacity was 205 mmfds., or 10 per cent. greater. When a number of such wires are hung up side by side the united capacity is always much less than that of the sum of each wire alone. Thus four wires, each 111 feet long and 0·215 cm. in diameter, were hung up 6 feet apart; the united capacity was found to be 583 mmfds., and not 820 or 4 × 205 mmfds. In the same way, 160 such wires suspended and insulated, the wires arranged in an inverted cone shape with angle of about 60°; the wires being 2 feet apart at the top and in contact at the bottom, were found to have a united capacity of 2685 mmfds., or only about 10 or 11 times that of one single wire of

[42] See "Handbook for the Electrical Laboratory and Testing Room," J. A. Fleming, vol. ii. chap. ii. p. 114.

the same length and diameter. The above figures show how difficult it is to obtain any very large capacity by suspending insulated sheets or wires of metal in the open air. If we attempt to multiply the sheets or wires, they simply reduce each other's capacity, and the sum total is very far below the sum of the individual capacities.[43]

As the case of a long thin wire insulated in air is important from the point of view of wireless telegraphy, we give another method of determining the capacity by calculation which is due to Professor A. Slaby.[44]

Let a circular-sectioned cylinder of metal have a length l and a diameter $2r$. Take the centre as origin and consider any slice of the cylinder of length dx at a distance x. Then let ρ be the density of the electric charge on the surface. Hence the surface charge on the ring of width dx is $2\pi r\rho dx$.

The potential $d\mathrm{V}$ due to this annular charge at the origin is—

$$d\mathrm{V} = \frac{2\pi r\rho dx}{\sqrt{r^2 + x^2}}$$

and since the potential in the cylinder is everywhere the same, we obtain the potential of the cylinder by taking the integral—

$$\mathrm{V} = 2\int_o^{\frac{l}{2}} \frac{2\pi r\rho dx}{\sqrt{r^2 + x^2}}$$

Now $$\int \frac{dx}{\sqrt{r^2 + x^2}} = \log_\epsilon \left(x + \sqrt{r^2 + x^2}\right)$$

Hence $$\mathrm{V} = 4\pi r\rho \left\{\log_\epsilon \left(\frac{l}{2} + \sqrt{r^2 + \frac{l^2}{4}}\right) - \log_\epsilon r\right\}$$

But $2\pi r\rho l$ is the whole charge Q on the cylinder, and by definition the capacity $\mathrm{C} = \frac{\mathrm{Q}}{\mathrm{V}}$. If, then, r is small compared with $\frac{l}{2}$, we have—

$$\mathrm{C} = \frac{l}{2 \log_\epsilon \frac{l}{r}} \qquad (94)$$

This is the same formula as (91).

8. Measurement of Small Capacities with High Frequency Electromotive Forces.—In the measurement of small capacities such as those of Leyden jars, antennæ and aerial conductors generally made with high frequency electromotive forces, there are some sources of error against which the experimentalist must be on his guard. If, for instance, the capacity of a Leyden jar of the ordinary type is measured with the rotating commutator as described in § 7, at a low frequency, that is, some frequency of the order of 100, and if the capacity of the same jar is subsequently measured with a high frequency, that is to say, a frequency of the order of a million more or less, a marked difference will in general be found between these two results. The capacity of such a small condenser with high frequency electromotive force can be best measured by the aid of the

[43] For additional information on this point, see Fleming and Clinton, "On the Measurement of Small Capacities and Inductances," *Phil. Mag.*, May, 1903, ser. 6, vol. 5, p. 493.

[44] See A. Slaby, "On Wireless Telegraphy," *Elektrotechnische Zeitschrift*, Aug. 1904; or *l'Éclairage Électrique*, Oct. 19, 1904, vol. 41, p. 179.

author's Direct Reading Cymometer (see Chap. VI. § 15). By means of this instrument the capacity can be measured easily for different high frequencies and with different electromotive forces. The principle on which high frequency measurement of capacity can be made has already been described in § 4 of this chapter. It consists in determining, by means of the cymometer, the frequency of the oscillations set up in a circuit composed of a known inductance and the capacity to be measured. Hence by varying the inductance we can vary the frequency for the same capacity, and if the condenser under test and the inductance form an oscillatory circuit with the spark gap, we can vary the charging electromotive force by varying the length of the spark gap. If we measure in this manner the capacity of a Leyden jar for frequencies varying, say, from 1 to 2 million, and with various spark gaps, say, from 1 to 4 mm., it will be found that the capacity of the Leyden jar increases with the length of the spark gap for the same frequency. The cause of this variation is the brush discharge which takes place at the edges of the tinfoil coating of the jar. When the Leyden jar oscillatory discharge is taking place an electric glow will be seen fringing the edge of the tinfoil. This really amounts to an escape of electricity from the tinfoil over the glass, and is equivalent to an increase in the capacity of the jar. This augmentation may amount to 5 or 10 per cent. of the capacity measured with a low frequency electromotive force, and is therefore by no means negligible. It can, however, be completely prevented by immersing the jar in highly insulating oil, so as to prevent glow discharge at the edges of the tinfoil. If a condenser is constructed of glass plates having tinfoil coatings put on in the usual manner, then no sensible variation in the high frequency capacity is found when the plates are immersed as described in oil when using varying values of the spark gap length, that is, of the charging electro-motive force.

On the other hand, with sufficient increase in frequency of the oscillations, the capacity is found to decrease when glow discharge is arrested by immersing the condenser in oil. The author has found that in comparing the capacity of a condenser with glass dielectrics at low frequency (100) and a high frequency (10^6), the difference in the capacity produced by the glow discharge at the edges of the tinfoil is far greater than the difference due to mere electrical frequency. This increase of capacity due to the glow discharge depends not merely upon the spark length employed in making the measurement, but also upon the frequency of the break of the induction coil, so that in measuring the capacity of Leyden jars by the cymometer, or any other method employing high frequency electromotive force, observers should always be careful to state the spark length, the spark frequency, and also the inductance of the circuit or the frequency of the oscillations.

As an instance of the kind of variations which may occur in such measurements, the following results are given of observations taken on the capacity of a Leyden jar of a size commonly used in wireless telegraphy. The capacity of this jar measured with the commutator at a frequency of 100 was found to be 0·001263 mfd. The capacity of the same jar was then measured with the author's cymometer for various spark lengths and inductances in series with the jar, as shown in the table below.

Table showing the Variation in Capacity of a Leyden Jar with Charging Voltage and Frequency.

Length of spark gap.	Spark voltage.	Inductance in centimetres $= L$.	Observed oscillation constant of circuit $= \sqrt{CL}$.	Calculated capacity of jar in microfarads. $= C$.	Frequency of oscillations used $= n$.
1 mm.	4600	5,000	2·55	0·001300	$1{\cdot}98 \times 10^6$
1 ,,	,,	10,000	3·65	0·001332	$1{\cdot}38 \times 10^6$
1 ,,	,,	15,000	—	—	—
				mean = 0·001316	
2 mm.	8100	5,000	2·60	0·001352	$1{\cdot}94 \times 10^6$
2 ,,	,,	10,000	3·69	0·001361	$1{\cdot}36 \times 10^6$
2 ,,	,,	15,000	4·52	0·001362	$1{\cdot}12 \times 10^6$
				mean = 0·001358	
3 mm.	11,400	5,000	2·70	0·001458	$1{\cdot}85 \times 10^6$
3 ,,	,,	10,000	3·77	0·001421	$1{\cdot}34 \times 10^6$
3 ,,	,,	15,000	4·60	0·001411	$1{\cdot}10 \times 10^6$
				mean = 0·001430	
4 mm.	14,500	5,000	2·72	0·001480	$1{\cdot}84 \times 10^6$
4 ,,	,,	10,000	3·81	0·001451	$1{\cdot}32 \times 10^6$
4 ,,	,,	15,000	4·71	0·001479	$1{\cdot}07 \times 10^6$
				mean = 0·001470	

The capacity of the same jar measured with low frequency $n = 100$ is 0·001263 mfds.

In this case the jar was not immersed in oil, and the difference shown between the high frequency measurements are largely dependent upon the different charging voltages used and irregularities in the break of the induction coil.

9. Variation of Dielectric Constant with Temperature and Time of Charge.—Dielectric constants are much affected (i.) by the temperature of the insulator, (ii.) by the charging voltage, and (iii.) by the mode and time of its application, viz. whether steady or reversed, and if reversed, on the speed of frequency of the reversals.

Just as the bending, twisting, or strain of an imperfectly elastic or semi-viscous solid under stress depends upon the temperature, stress, and mode of application of the stress, so is it in the electrical case. The lower the temperature, the shorter the time of application of the electric force, the smaller, generally speaking, do we find the value of the dielectric constant. Observers, however, have not been always careful to define the manner in which their experiments have been conducted, and hence we find great differences between the recorded values of the dielectric constant assigned to any one substance.

For a very large number of solid insulators the dielectric constant is approximately equal to 2·6 times the density. When, however, we examine various solvents, such as water, alcohol, glycerine, nitrobenzol, etc., we find that the introduction into a chemical molecule of certain radicles or atomic groups, such as hydroxyl (HO), nitryl (NO), and ammonyl (NH_2) has the effect of creating at normal temperatures abnormally large dielectric constants. Thus the dielectric constant of

pure water at ordinary temperatures is about 80, and that of ethylic alcohol is 25. Chemically speaking, water is a hydrate of hydrogen, H(HO), and alcohol is ethylic hydrate, $C_2H_5(HO)$.

The discovery was, however, made by Sir James Dewar and the author, working together, that extremely low temperatures, such as that of liquid air, had the effect of greatly reducing these abnormally large dielectric constants.

As regards temperature change, with few exceptions, we can say that decrease of temperature decreases the dielectric constant. Also that decrease in the time of charging or application of the electric force decreases dielectric constant. This is well shown by a series of observations by MM. J. Curie and P. Compan.[45] They measured the dielectric constant of three samples of crown glass in the form of sheet at temperatures between 13° C. and that of liquid air −185° C., and for various times of charging from 10 seconds to 0·05 of a second, and the results are tabulated below.

Dielectric Constant of Crown Glass as affected by Temperature and Time of Charging.

Duration of charge in seconds.	Temperature, 13° C.	Temperature, 0° C.	Temperature, −19° C.	Temperature, −75° C.	Temperature, −185° C.
10	11·25	9·47	8·44	7·09	6·49
1	9·32	8·44	7·81	7·09	6·49
0·1	8·04	7·75	7·42	7·09	6·49
0·05	7·85	7·50	7·36	7·09	6·49

In the above case the variation of the dielectric constant (K) with temperature can be expressed by a simple linear formula—

$$K = K_0 + AT$$

where K_0 is the dielectric constant at absolute zero, T is the absolute temperature, and A is a constant. For three samples of crown glass, Curie and Compan is found—

K_0.	A.
6·03	0·00524
6·83	0·00520
6·24	0·00535

Similar results were found with ebonite, mica, and quartz.

It is evident, therefore, that the variation of dielectric constant (D.C.) with time of charging disappears at very low temperatures. An extensive series of experiments on the dielectric constants of various bodies at very low temperatures was carried out by Sir James Dewar and the author in 1896 and 1897, the results of which were published in the *Proceedings of the Royal Society of London*. The following is a list of the published papers :—

(1) "On the Dielectric Constant of Liquid Oxygen and Liquid Air," *Proc. Roy. Soc.*, vol. 60, p. 360.

(2) "Note on the Dielectric Constant of Ice and Alcohol at very Low Temperatures," *Proc. Roy. Soc.*, vol. 61, p. 2.

(3) "On the Dielectric Constants of Pure Ice, Glycerine, Nitrobenzol, and

[45] See *Comptes Rendus*, June, 1902, vol. 134, p. 1295, "Sur le pourvoir Inducteur Spécifique des diélectriques aux basses Temperatures."

Ethylene Dibromide at and above the Temperature of Liquid Air," *Proc. Roy. Soc.*, vol. 61, p. 316.

(4) "On the Dielectric Constant of Certain Frozen Electrolytes at and above the Temperature of Liquid Air," *Proc. Roy. Soc.*, vol. 61, p. 299. This paper describes the cone condenser and methods used.

(5) "Further Observations on the Dielectric Constants of Frozen Electrolytes at and above the Temperature of Liquid Air," *Proc. Roy. Soc.*, vol. 61, p. 381.

(6) "The Dielectric Constants of Certain Organic Bodies at and below the Temperature of Liquid Air," *Proc. Roy. Soc.*, vol. 61, p. 358.

(7) "On the Dielectric Constants of Metallic Oxides dissolved or suspended in Ice cooled to the Temperature of Liquid Air," *Proc. Roy. Soc.*, vol. 61, p. 368.

(8) "A Note on some Further Determinations of the Dielectric Constants of Organic Bodies and Electrolytes at very Low Temperatures," *Proc. Roy. Soc.*, vol. 62, p. 250.

The general results of all these observations was to show that reduction of temperature lowered the dielectric constant, in some cases in a very marked degree. Also they showed that the result of increasing the frequency when using an alternating electromotive force was to reduce the dielectric constant, in some instances in the most marked manner, but in other cases hardly at all.

In a later chapter we shall discuss the relation between dielectric constant and optical refractive index, known as Maxwell's law. According to this law the dielectric constant K should be numerically equal to the square of the refractive index, μ^2, in those cases in which the magnetic permeability is equal to that of air. If, however, we take μ to be the optical refractive index, then exceptions are far more numerous than the coincidences with the law.

The great majority of liquid and solid dielectrics at ordinary temperatures do not obey Maxwell's law, but it was shown by the investigations of the above-named authors that when cooled to very low temperatures the abnormally large values of some dielectric constants disappeared and are brought into much closer agreement with the square of the optical refractive index. The following table shows some of the results obtained by Fleming and Dewar:—

Dieletric Constants (K) at Different Temperatures taken with Alternating Electric Force having a Frequency of 120.

Substance.	K at 15° C.	K at −185° C.	Square of optical refractive index.
Water	80	2·4 to 2·9	1·779 for D line
Formic acid	62	2·41	—
Glycerine	56	3·2	—
Methyl alcohol	34	3·13	—
Mononitrobenzol	32	2·6	—
Ethyl alcohol	25·8	3·11	1·831
Acetone	21·85	2·62	—
Ethyl nitrate	17·72	2·72	—
Amyl alcohol	16·0	2·14	1·951
Aniline	7·51	2·92	—
Castor oil	4·78	2·14	2·153
Ethylic ether	4·25	2·31	1·805
Olive oil	3·16	2·18	2·131
Carbon bisulphide	2·67	2·24	2·01
Petroleum oil	2·07	—	2·075
Turpentine	2·23	—	2·128
Benzol	2·38	—	2·26

B. B. Turner determined with great care the dielectric constants of certain pure liquids, which are given in the table below and agree fairly well with those in the preceding table.[46]

Substance	Dielectric constant K at 18° C.
Water	81·07
Nitrobenzol	36·45
Orthonitrotoluol	27·71
Ethyl chloride	10·90
Aniline	7·298
Ether	4·367
Metaxylol	2·376
Benzol	2·288

The values obtained for the dielectric constants of various well-known solid insulators differ very much, but the following table gives some accepted values :—

Dielectric Constants of Various Solid Insulators.

Substance.	Dielectric constant K at 15° C.	Square of optical index of refraction μ.
Flint glass (dense)	10·1	2·924
,, ,, (light)	6·57	2·375
Crown ,, (hard)	6·96	—
Calcite	7·7	2·734 A
Fluorspar	6·7	2·05
Mica	6·64	2·526
Tourmaline	6·05	2·63
Rock salt	5·85	2·36
Quartz	4·55	2·41
Sulphur	2·9 to 4·0	4·89 B
Shellac	2·7 to 3·0	—
Ebonite	2·05 to 3·15	—
Indiarubber (pure brown)	2·12	—
,, (vulcanized)	2·69	—
Paraffin wax	2·0 to 2·3	—

Values given for the dielectric constant of various substances by different observers differ considerably, and as the circumstances of the measurement with respect to the time of charging and the electric force used have not been identical, we cannot consider the so-called "constant" as more than an exceedingly rough guide in the predetermination of capacity. Particularly is this the case with regard to glass. This material is of very variable composition, and its dielectric constant, according to some observers, varies very much with the time of charging. Hence, caution must be taken not to apply indiscriminately the results of low frequency dielectric measurements in high frequency work.

M. v. Hoor has carried out investigations on the effect of variation in the electric force employed on the resulting measured dielectric constant. The electric force was measured in volts per centimetre of thickness, that is, by dividing the charging voltage by the thickness

[46] See *Zeitschrift für Phys. und Chem.*, 1900, vol. 35, p. 385; also *Science Abstracts*, vol. 4, p. 503.

of the dielectric. The results for some dielectrics are given below[47]:—

VARIATION OF DIELECTRIC CONSTANT WITH ELECTRIC FORCE.

Substance.	Electric force in volts per centimetre.	Dielectric constant.
Paraffined paper	55·5	3·65
,, ,, ...	0·528	3·68
Crown glass, No. 1	22·9	10·7
,, ,, ,, ...	4·46	12·8
Crown glass, No. 2	27·2	6·92
,, ,, ,, ...	1·037	7·22
Guttapercha	41·000	3·155
,, ...	0·491	3·26
Megohmit	5·95	5·09
,, ...	0·286	5·31

It will be seen that there is a considerable variation in the case of glass, the dielectric constant increasing as the electric force diminishes. In connection with this, it is worth while to note that the variation of conductivity in dielectrics is in the same direction. It has been found that for most insulators the insulation resistance decreases as the applied electromotive force increases.[48]

In these respects glass has a disadvantage as a dielectric compared with ebonite, as far as its use with high frequency currents is concerned.

Another very important cause of variation in dielectric constant is the frequency of electric force. It is evident we may take the ratio of electric displacement to electric force either with a steady electric force, uniformly acting in one direction, or with a periodically reversed electric force, having any assigned frequency. In the case of some dielectrics, such as ebonite or sulphur, there is usually said to be very little difference between the dielectric constant found with low frequency alternating electric force and that under high frequency electric force. On the other hand, with glass there is said to be a very marked difference, according to the experiments of many observers, with the exception, however, of Pollock and Vonwiller, who deny that glass exhibits any very marked variation of dielectric constant with frequency. This was confirmed by Dr. J. Hopkinson and Professor E. Wilson, who say that the dielectric constant of English light flint glass is constant for low frequencies and up to a frequency $n = 2 \times 10^6$ (see *Phil. Trans. Roy. Soc. Lond.*, 1897, vol. 189, p. 109).

The author has, however, found that both glass and ebonite give evidence of a decrease in dielectric constant with frequency, and that only liquid hydrocarbons can be considered as having a dielectric constant independent of the frequency.

[47] See *Elektrotechnische Zeitschrift*, vol. 22, p. 716; or *Science Abstracts*, vol. v. p. 32.

[48] See A. W. Ashton, "On the Resistance of Dielectrics and on the Effect of an Alternating Electromotive Force on the Insulating Properties of Indiarubber," *Phil. Mag.*, 1901, ser. 6, vol. 2, p. 501.

It has been found, both by Professor Sir J. J. Thomson and by M. R. Blondlot, that at a frequency of 25×10^6 the dielectric constant of glass has a value as low as 2·7 or 2·8. For a low frequency of steady force, the value, as shown by the tables already given, is from 6 to 10.[49]

Again, all observers who have determined the dielectric constant of water or ice with low frequency force, say between 1 and 200 alternations of electric force per second, have found a value for the dielectric constant not far from 80.

If, however, the dielectric constant of ice is determined at $-185°$ C. with a frequency of 120~, then its dielectric constant is found to be about 2·4 to 2·9. In some cases, such as ethylic alcohol, a very moderate increase in the frequency suffices to sensibly reduce the dielectric constant.

It has been pointed out by Fleming and Dewar that reduction of temperature, even when operating with low frequency alternation of electric force, has the same effect as an increase of frequency alone at constant ordinary temperature in reducing the abnormally large dielectric constants of certain bodies to a value more in accordance with Maxwell's law.

For these reasons, therefore, glass is a dielectric not very suitable for making condensers to be employed in exact scientific work with high frequency currents.

Its cheapness, however, and other good electrical and mechanical qualities, make it a very convenient substance to use for commercial work.

10. Dielectric Hysteresis.—The question of the energy dissipation in dielectrics under rapidly reversed electric forces is one which has been much studied.[50] In the case of a perfect dielectric used as the insulator of a condenser there should be no internal dissipation of energy by charge and discharge. If the alternating electric force is sinoidal, then the capacity current should be also of the same form and 90 degrees different in phase, the current being in advance of the electromotive force. The power factor, or cosine of the angle of phase difference, should therefore be zero. As a matter of fact, in the case of most actual condensers the power factor is not zero, and when subjected to alternating electromotive force they rise in temperature, and this points to some internal cause of energy dissipation in the dielectric. This has generally been attributed without discrimination to *dielectric hysteresis*.

It is, however, necessary in the first place to distinguish carefully between energy loss due to true resistance, electrolytic action, or electric discharges, and that (if any) involved in simply creating change of dielectric polarization or electric displacement. It is a matter of great difficulty to free any insulator so completely from

[49] See Prof. Sir J. J. Thomson, *Proc. Roy. Soc.*, 1889, vol. 46, p. 293, "On Specific Inductive Capacities of Dielectrics under Rapidly Alternating Electromotive Force"; also M. R. Blondlot, *Comptes Rendus*, 1891, vol. 112, p. 1058. Compare, however, with Pollock and Vonwiller, *Phil. Mag.*, 1902, ser. 6, vol. 3, p. 586.

[50] For a fairly full *résumé* of knowledge on this subject up to 1895, see a paper by P. Gasnier in *The Electrician*, Nov. 1, 1895, vol. 36, p. 7.

water and air or electrolyzable material that under alternating electric force no heat is produced in it by true joulean action. It has been considered that this could be eliminated by making a measurement first with alternating electromotive force and then with continuous current at the same R.M.S. voltage, and employing a voltmeter to measure the power taken up in both cases.

The first measurement is then assumed to give the total losses, and the second the C^2R, or heating losses, and also the electrolytic losses. This method was adopted by Mr. Steinmetz,[51] and he came to the conclusion that there was a true dielectric hysteresis loss, varying as the square of the electromotive force. There are objections to this method, on the ground that the resistance of a dielectric is an ill-defined quantity, and in any case is a function of the voltage and time of application. Moreover, loss by creeping over the surface of the dielectric or brush discharges at the edges of the electrodes is not eliminated. In the same manner measurements of power factor by the wattmeter, or measurements of the angle of lag made on open circuited cables, may give a value of the total loss due to all causes in the insulator of a cable, but they do not settle the question whether there is an energy dissipation due simply to change in the polarization or electric strain, analogous to true magnetic hysteresis in iron. In fact, just as we must distinguish between true magnetic hysteresis and eddy current loss, so in the case of insulators we must distinguish between that which may properly be called "dielectric hysteresis" and other sources of energy dissipation. Another mode of procedure was suggested by Ricardo Arno.[52] He placed a cylinder of an insulating material in a rotating electrostatic field, and found that it was set in rotation. Professor R. Threlfall has also conducted an extensive and well-devised series of experiments with a modification of Arno's apparatus, and carefully examined various sources of error.[53] Threlfall used his dielectrics in the form of ellipsoids of revolution and created the rotating field by mechanically rotating a sort of air condenser with a steady uniform field. Between the plates of this condenser the ellipsoid was suspended. He carefully dried the surface of the dielectric and suspended it by a quartz fibre, and shielded the mirror and attachments from electrostatic action. Out of a very large number of experiments on ebonite, sulphur, resin, and other dielectrics, he came to the following conclusions :—

(i.) When an ellipsoid of a solid dielectric is placed in a rotating electric field, it is set in rotation even when all sources of true electric conduction are eliminated. This indicates that the electric strain or polarization lags behind the electric force in phase. Hence, in one sense, this is a "hysteresis" effect.

(ii.) The effect is absent in liquid dielectrics.

(iii.) In solid dielectrics, if we denote the internal electric force

[51] See C. P. Steinmetz, *Electrical Engineer*, New York, March 16, 1892; or *The Electrician*, London, 1892, vol. 28, p. 602.

[52] See R. Arno, *Accademia dei Lincei*, Oct. 6, 1892, and April 30, 1893. See *The Electrician*, 1893, vol. 30, p. 516; vol. 31, p. 201; vol. 32, p. 222; vol. 33, p. 210.

[53] See R. Threlfall, "On the Conversion of Electric Energy in Dielectrics," *Physical Review*, 1197, vol. iv. p. 457; vol. v. p. 21.

by F, and the energy expenditure due to the true dielectric hysteresis by W, then—

$$W = \alpha F^n$$

The exponent n is a number lying between 1·5 and 1·95 for ordinary homogeneous dielectrics, but it is not exactly 1·6.

(iv.) This hysteresis loss is very valuable in passing from specimen to specimen, and an exact value cannot be assigned to any *substance* as contrasted with a *specimen*.

(v.) As regards the factor α, it is a very small number in the case of paraffin wax, but in the case of glass and ebonite may approach a value 0·03 or 0·04. Thus for a particular sample of ebonite the formula found was—

$$W = 0{\cdot}029\ F^{1{\cdot}163}$$

and for a flint-glass spheroid—

$$W = 0{\cdot}038\ F^{1{\cdot}92}$$

whilst for a paraffin ellipsoid—

$$W = 0{\cdot}0008\ F^{1{\cdot}56}$$

The constant α varies according to Threlfall greatly from sample to sample, but the index n is much more constant for samples of the same material, but varies from material to material.

This loss can be expressed as a percentage of the energy stored per unit of volume. For if F is the uniform internal electric force in one unit of volume, then the energy stored is $\frac{1}{2}CF^2$ where C is the capacity per unit of volume. But $C = \frac{K}{4\pi}$ for unit volume, hence the energy stored $T = \frac{KF^2}{8\pi}$.

But the energy expended in hysteresis is $W = \alpha F^n$, therefore—

$$\frac{W}{T} = \frac{8\pi\alpha}{K} F^{n-2} = \beta\,(\text{say})$$

Let F = 1, then—

$$\beta = \frac{8\pi\alpha}{K}$$

Taking the case of sulphur, Threlfall gives the following figures: $K = 3{\cdot}162$, $\alpha = 0{\cdot}0139$, $n = 1{\cdot}91$. Hence $\beta = 0{\cdot}1112$, or nearly 11 per cent.

For ebonite, $K = 3{\cdot}5$, $\alpha = 0{\cdot}029$, $n = 1{\cdot}765$, and $\beta = 0{\cdot}212 = 21{\cdot}2$ per cent. The above ratio denoted by β must not be confused with the ratio of the total dielectric energy dissipation to the volt-amperes or product of the condenser current and impressed voltage. This last is the power factor (P.F.) of the condenser. Taking sinoidal variation of condenser current and voltage, and assuming no energy loss except the true hysteresis, we have the volt-amperes per unit volume in equivalent electrostatic measure given by CpF or by $\frac{K}{4\pi} 2\pi n F = \frac{K}{2} F$. Hence for unit internal force the power factor (P.F.) is equal to $\frac{2W}{K}$ or to $\frac{2\alpha}{K}$.

For the sulphur mentioned above this gives P.F. = 0·009, and for ebonite P.F. = 0·017.

Threlfall also made experiments with an apparatus designed by Ebert for producing a very high frequency revolving electric field, and placed various solid dielectrics in it. There is no need to describe the apparatus in detail, for this the reader must refer to the original paper.[54] The results, however, showed that for a frequency as high as 10^7 dielectric hysteresis was absent. This result shows that any heating of condensers which occurs with high frequency currents must be due to electric conduction, electrolysis or discharges over the surface, and not to true dielectric hysteresis.

In regard to the general question of dielectric hysteresis, Professor A. W. Porter and Dr. D. K. Morris have pointed out that it is necessary to distinguish between merely viscous effects and true hysteresis.[55] If an electric force is applied to a dielectric it may take time to establish the corresponding electric strain, in which case viscosity is present. On the other hand, the strain may have the same value whether it has been arrived at by descending from a large force or rising up from a small one to the same value. In this last case true hysteresis is absent. In experiments made with a particular mica condenser, Porter and Morris found dielectric viscosity but no true dielectric hysteresis. If viscosity is present, it follows that when the impressed force varies in value but not direction the resulting flux value is a function of the frequency. In the case of magnetism, it has been shown that the permeability is less as the speed of alternation of the force increases. So also, in the case of dielectrics, there seems clear evidence that the dielectric constant does decrease in value as the frequency of the electric force increases. E. E. Northrup [56] measured the dielectric constant of paraffin and of a variety of glass for frequency two values not precisely stated, but called respectively high and low.

Northrup found values of the dielectric constant K as follows :—

Paraffin wax (melting point 54° C.)	K = 2·32 low frequency.
,, ,, ,, ...	K = 2·25 high ,,
Glass	K = 6·25 low frequency.
,, ...	K = 5·86 high ,,

On the other hand, there is no doubt that in the majority of dielectrics the presence of moisture and conducting particles or heterogeneity of structure gives rise to true conduction currents in the mass of the dielectric, and therefore to an energy dissipation. In the case of high frequency currents, it is to this surface creeping, internal discharge or conduction, that we must look for a source of energy waste and dielectric heating, and not to true dielectric hysteresis. Experiment shows that in the case of English flint glass, when used as the dielectric of condensers for high frequency currents,

[54] See Ebert, *Wied. Annalen*, 1894, vol. 53, p. 144.

[55] Porter and Morris, *Proc. Roy. Soc.*, 1895, vol. 57, p. 469; also *The Electrician*, April 12, 1895, vol. 34, p. 735.

[56] E. E. Northrup, "A Method for comparing the Values of the Specific Inductive Capacity of a Substance under Slowly and Rapidly Varying Fields. Results for Paraffin and Glass," *Phil. Mag.*, 1895, vol. 39, 5th ser. p. 78.

there is a sensible internal energy loss, even if the brush discharges from the edges of the coatings are prevented by immersing the condenser in highly insulating oil.

11. The Measurement of High Frequency Electric Currents. Hot Wire Ammeters.—In dealing with electric oscillations and high frequency currents we require special forms of ammeter for making the required current measurements. In some cases instruments can be employed for comparative measurements which depend for their action upon the production of a magnetic field round the conductor through which these oscillations pass. In this case the oscillations have to pass through an insulated wire wound up into some form of coil. It is, however, difficult to graduate such instruments so as to make their scales read correctly the mean-square or effective value of oscillatory currents of various frequencies sent through the coil. This arises from the fact that with high frequency currents in close coils of insulated wire a considerable dielectric current passes from coil to coil, and is, so to speak, shunted out of the wire to a degree depending upon the frequency. Hence, as a rule, coil or electro-magnetic instruments are not so suitable as those of the straight hot-wire type for the direct measurement in amperes of a high frequency current. It is not, however, every form of hot-wire ammeter which is available for the purpose. Most hot-wire ammeters in use for measuring continuous or low frequency alternating currents are constructed on the shunt principle. The main part of the current flows through a fixed coil on metal strip, and a shunted portion passes through a bye-pass wire, which is thereby heated, expanded, and provides the means of indication or measurement. This shunted circuit is, however, inadmissible in the case of measurement of high frequency currents. The ratio in which the current is divided between the shunt and working wire is a function of the frequency. Accordingly the only form of ammeter which is available and accurate for the measurement of high frequency electric currents is the hot-wire ammeter, in which the whole current passes through the working wire of the instrument.

Even then certain other precautions are necessary. The wire used must not be contained in a metal case or tube, and if it is a single wire, should not be thicker than 0·25 mm., so that its high frequency resistance is identical with its ordinary or steady resistances. Hence, if the working wire has to carry a current of several amperes, it must be made up of a sufficient number of separated or insulated fine copper or platinoid wires arranged in a bundle or strand, not closely compressed, but open. The best plan is to use thin bare wires slightly separated from each other. The stranded wire is stretched between two fixed points, and the expansion produced by the high frequency current traversing it then creates a sag, which is measured by some indicating needle.

A form of high frequency hot-wire ammeter devised by the author is made as follows:—

On a vertical hardwood board are fixed two metal pins, A and B, between which are stretched with equal tightness a number of fine copper or platinoid wires. They are kept taut by a metal loop drawn back by a spiral spring, O (see Fig. 26). A second fine wire

is also stretched between the point C and another fixed pin, D, and to the centre of this last wire is attached a third wire, EF, the upper end of which is fastened to the short arm of a pivoted index needle. When electric oscillations are passed through the wires AB, they expand and sag, and this creates a still greater sag in the wire CD, and hence allows the short end of the index needle to rise, and the pointer end to move down over a scale. By passing various measured continuous currents through the wires AB, the scale of this instrument can be graduated directly to read amperes. Hence, if any high frequency current or steady groups of oscillations are passed through the parallel wires, the needle indicates at once their root-mean-square value. By suitably selecting the length and number of the working wires of the instrument, it can be adapted for any range of measurement. For the measurement of very small high frequency currents,

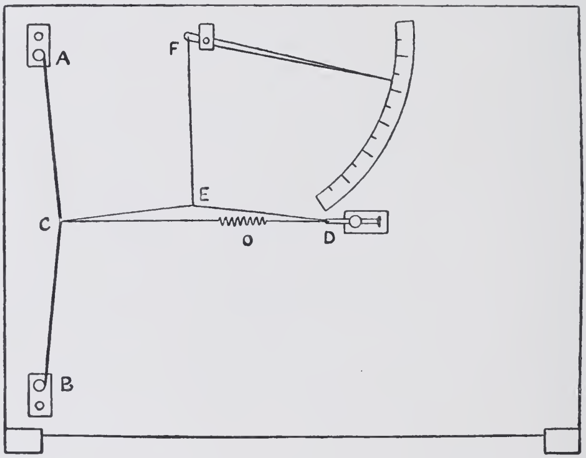


Fig. 26.—Hot-wire Ammeter for High Frequency Currents. (Fleming.)

such as those of about 0·01 to 0·1 ampere, the author has devised another form of single wire hot-wire instrument,[57] and a hot-wire voltmeter on the same principle had been previously but independently described by Professor Threlfall.[58]

The following form of hot-wire ammeter can be so made as to measure currents as small as 2 milliamperes, and is easily calibrated at the time of using it.

The ammeter consists of a wooden box (AB, see Fig. 27), 104 cms. in length, 8 cms. in height, and 6 cms. in width. The top of this box opens on hinges, and in the centre is fixed an achromatic convex lens, *l*, having a focal length of 10 cms. The front of the box is cut down to form a window, W, which is glazed with a sheet of thin

[57] See J. A. Fleming, "On a Hot-wire Ammeter for the Measurement of Very Small Alternating Currents," *Phil. Mag.*, May, 1904, ser. 6, vol. 7, p. 595; or *Proc. Phys. Soc. Lond.*, 1904, vol. 19, p 173.

[58] See R. Threlfall, "On a New Form of Sensitive Hot-wire Voltmeter," *Proc. Phys. Soc. Lond.*, 1904, vol. 19, p. 58; also *Phil. Mag.*, ser. 6, vol. 7, p. 371, 1894.

transparent mica (see Fig. 27). In the box is fixed a square rod of well-seasoned pine, 1 metre in length and 2·5 cms. in width and breadth. To each end of this rod are fixed two small brass uprights to which terminal screws are attached, and also small spring pieces of brass, *p*, *p*, which are pressed in by screws passing through the uprights.

To these springs at each end of the rod are attached fine wires, either of pure silver or of some high resistance alloy, such as constantan, platinoid, etc., according to the use to which the instrument is to be placed.

In the instrument constructed by the author, these wires are of platinoid, the length of the wires being 1 metre and the diameter 0·05 mm. The distance apart of these wires is about 5 mm. The extremities of these wires are soldered to the two spring pieces at the ends of the wooden rod, and the tension of these wires can be adjusted

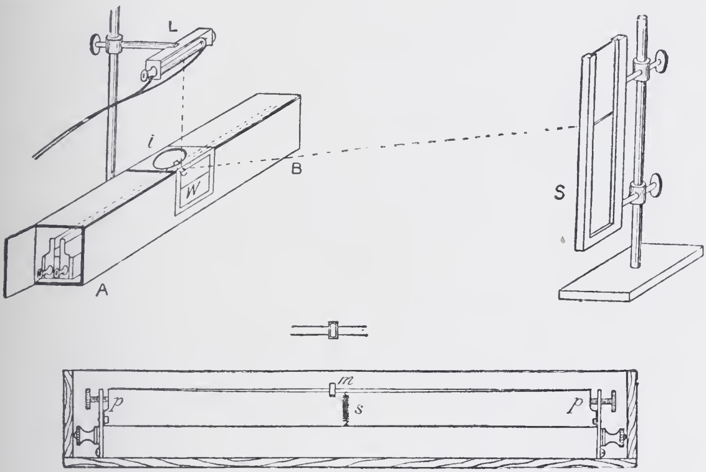


FIG. 27.—Hot-wire Milliammeter. (Fleming.)

by means of the screws passing through the small uprights and pressing against the spring pieces.

To the centre of the wooden rod carrying the above-mentioned fine wires are fastened two very delicate spiral springs, *s*, which have their other ends looped over the long straight wires. These spiral springs are made of extremely fine platinoid wire, and they serve to keep the ammeter wires tight.

If one of the wires is heated by passing a current through it, it sags down slightly. This sag is indicated in the following manner :—The two wires are embraced by an exceedingly small loop of paper, *m*, made from a strip of paper 2 mm. in width and about 12 or 15 mm. in length.

To this loop of paper is attached with a touch of shellac a fragment of silvered microscopic glass about 2 mm. in width and 5 mm. in length.

The tension of one of the wires is so adjusted that when no

current is passing through either of them one wire sags more than the other, and this little loop of paper and its attached mirror sets itself at an angle of about 45 degrees to the horizontal. This is attained by slightly relaxing the tension on one of the wires. Upon the lid of the containing box is carried an incandescent lamp, having a straight or horseshoe-shaped filament, and in front of the box is placed a vertical strip of ground glass, S, carried in a brass grooved frame, which can be adjusted to any height on a vertical metal rod. The height of the incandescent lamp is so adjusted that the lens forms a clear image of the filament or of one leg of the filament upon the ground glass in the form of a horizontal line of light. With a good lens this image can be made very sharp. The lens actually used was the objective of an old opera-glass. A hood of metal or asbestos placed over the lamp prevents the direct rays of the lamp falling on the ground-glass screen. The screen can be conveniently placed about a metre from the wire box.

If, then, a small current is passed through the slacker of the two measuring wires, its sag will increase and the small mirror attached to the two wires will be tilted, and the image of the filament on the ground glass will move down, but return again to its original zero, as soon as the current is removed.

As a preliminary step, both the wires must be aged by sending intermittently a small current through them for a considerable time, this current being continually interrupted.

In the instrument actually made, the platinoid wires have a resistance of about 168 ohms each; hence, if an electromotive force of 2 volts is applied to the ends of the wires, a current of about $\frac{1}{84}$ of an ampere passes through them.

The instrument is calibrated in the following manner:—A secondary cell having a measured electromotive force, say, of about 2 volts is connected in series with one of the working wires through a resistance box of the usual plug pattern. By varying this resistance, different currents are passed through the wire, and the position of the spot of light on the screen corresponding to the different currents is noted.

If the wire employed is of platinoid or of constantan, its resistance will not be altered appreciably by different small currents passed through it, and hence the resistance of the wire can be determined once for all, with a sufficient degree of approximation for practical purposes, by means of a potentiometer. When this has once been done, a few observations taken with a cell of known electromotive force and a plug resistance box used as above, enable the observer to mark off on the ground-glass strip with a pencil the position of the line of light for various known currents lying within a certain range. The strip of ground glass may then be removed and applied to a sheet of squared paper, and a curve plotted down showing the deflections in terms of the actual currents. This curve proves to be a parabola (see Fig. 28), because, if we plot the logarithms of the deflections and the logarithms of the currents, we have a straight line delineated, making an angle with the horizontal, the tangent of which is equal to 2. If, then, we replace the ground-glass screen in its original position and pass through the ammeter wire any current, continuous or alternating, lying within the range of the graduation, the resulting deflection

of the line of light on the screen can be at once marked off on the ground glass, and from the curve of calibration obtained as above described the ampere value of this current becomes at once known.

In the instrument actually used the deflection of the line of light on the scale placed at a distance of about 80 cms. from the mirror, produced by an application of 2 volts to the wire, is about 3 cms., and

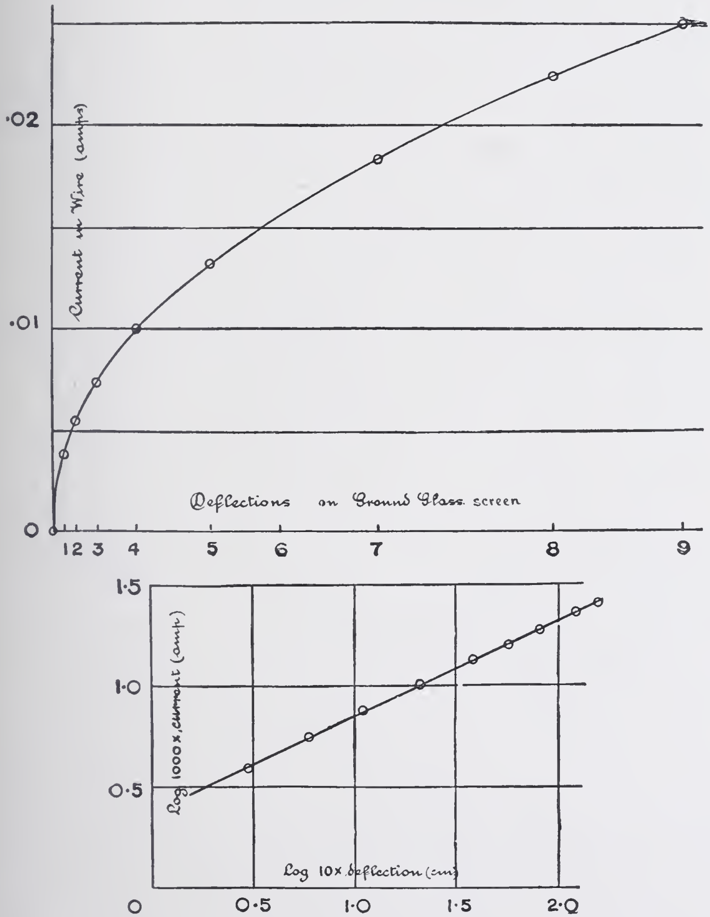


FIG. 28.—Calibration Curves of a Hot-wire Ammeter.

4 volts produce about 12 cms. deflection; hence, current of about $\frac{1}{100}$ of an ampere, or 10 milliamperes, produces a deflection which can be accurately read to within 2 or 3 per cent., and a current as small as 5 milliamperes thus can be measured.

The particular class of wire with which the instrument should be strung depends on the uses to which it is to be put. If the object is to read a current of as small a value as possible, then the wire must

be as fine as possible, and made of a material of high specific resistance, such as constantan.

Messrs. Hartmann and Braun, of Frankfurt, have recently given attention to the production of very fine wires drawn from different pure metals and alloys, and they are able to furnish wires of pure metals and high-resistance alloys drawn down to diameters varying between 0·05 mm. and 0·02 mm. The resistance of a constantan wire of the latter size per metre is about 1350 ohms, whilst a wire of pure silver of the larger size has a resistance of only 8 ohms per metre.

The sag of the wire used in the above-described instrument depends essentially upon its temperature, and its temperature depends upon the rate at which energy is being expended in it, per unit of its surface. Accordingly, for the measurement of the smallest currents the wires must be of high-resistance material and as small as possible in diameter, whilst for the measurement of small voltages the wire must be made of a material like silver with high conductivity.

The resistance R of the ammeter wire corresponding to different currents, A, through it can be determined as follows: The ammeter wire is joined in series with a plug resistance, R_1, and also with a constant resistance, R_2, which may be either 20 or 40 ohms.

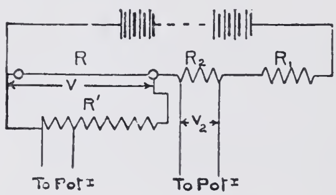


FIG. 29.

The ammeter wire is also shunted by a divided resistance, R′ (Fig. 29), and from a section of this resistance and from the terminals of the resistance R_2 wires are taken to a potentiometer. A battery of 100 volts is connected up, so as to send a small current through the ammeter wire, and this is adjusted until the terminal potential difference of the ends of the ammeter wire is either 2, 4, or 6 volts as required. Let this last potential difference be called V, and the P.D. down the resistance R_2 be called V_2. Also let the resistance of the ammeter wire under the working circumstances be R. Then $\frac{V}{R}$ is the current through the ammeter wire, and $\frac{V}{R'}$ the current through the divided resistance, and the sum $\frac{V}{R} + \frac{V}{R'}$ is equal to $\frac{V_2}{R_2}$, which is measured. Hence R can be determined corresponding to various values of $\frac{V}{R}$.

For measuring even smaller high frequency currents, Mr. W. Duddell[59] has devised an ingenious instrument, which is, in fact, an application of Boy's microradiometer. A small rectangular circuit, F (Fig. 30), is suspended by a quartz fibre, S, in the field of a strong magnet, M, and the ends of this coil terminate in a bismuth antimony thermocouple, T, one junction of which rests over and just clear of

[59] See Mr. W. Duddell, "On Some Instruments for the Measurement of Large and Small Alternating Currents," *Proc. Phys. Soc. Lond.*, 1904, vol. 19, p. 233.

a thin strip of metallic foil or a wire, AB, through which the current to be measured is passed (see Fig. 30). The heat generated in this strip acts by convection and radiation on the thermo element, and creates in the associated circuit a current which causes it to be deflected in the magnetic field in which it is suspended. By attaching a mirror to this movable coil, Mr. Duddell has been able to measure alternating currents having a root-mean-square value of less than $\frac{1}{10000}$ of an ampere. This instrument has proved of use in measuring the oscillatory currents in wireless telegraph antennæ.

For this purpose Mr. Duddell has employed thin strips of gold leaf as the heating circuit placed under the thermopile, and through this strip the electric oscillations pass and create in it heat, and

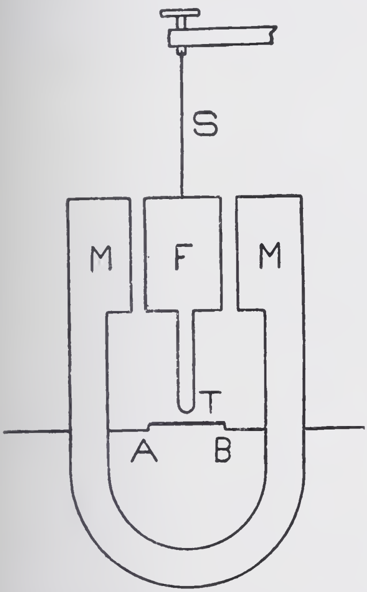


Fig. 30.—Principle of the Duddell Thermo-galvanometer.

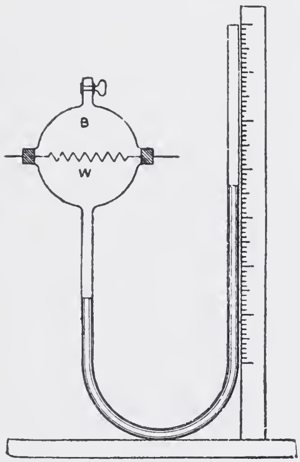


Fig. 31.—Snow-Harris or Riess Hot-wire Ammeter.

enable a measurement to be made of their root-mean-square or effective value. It is easy to detect and measure the effective (R.M.S.) value of the current produced by a Bell telephone, when suitably spoken into, by the aid of this Duddell thermo-galvanometer.

Another method of employing a wire heated by electrical oscillations for the measurement of their effective or root-mean-square value has been much used in Germany. It is an application of a well-known instrument, usually called the Riess electric thermometer. It was originally invented by Sir. W. Snow-Harris in 1827 (see *Phil. Trans. Roy. Soc.*, 1827). In its modern form it consists of a glass bulb (B) or tube (see Fig. 31), enclosing a fine wire (W) or stranded bundle of fine wires, with suitable electrodes. To the bulb is connected a **U**-tube having liquid in it, and also a lateral tube with glass stopcock is attached to the bulb for the purpose of equalizing

the air pressure within and without. If an electric current is passed through the wire it heats it, and if the current remains constant a condition is soon reached in which the air in the bulb gains as much heat per second from the wire as it loses by radiation and convection. Then the pressure of the air in the bulb becomes steady, and is higher than that of the external air. Accordingly, the manometer liquid rises in one limb of the U-tube and falls in the other. A scale can be attached which shows the position of the liquid when various currents reckoned in amperes are passed through the wire. Since currents with equal R.M.S. value produce equal heat in the wire in the same time, the instrument becomes a means for measuring the R.M.S. value of electric oscillations or trains of oscillations. This instrument has to be used with some precautions to avoid errors due to expansion of the air in the bulb by heat other than that created in the wire, and is not generally so much to be trusted as a hot-wire

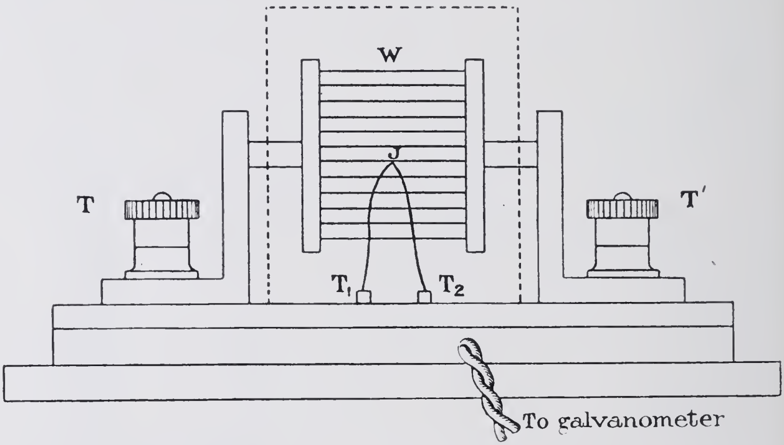


Fig. 32.—Hot-wire Thermo-electric High Frequency Ammeter. (Fleming.)

ammeter of the type just described, in which the heating effect of the current produces a sag in a wire strained between two fixed points.

The most generally useful type of hot-wire ammeter for the measurement of high frequency currents is one in which we determine the mean-square value of the current passing through the wire by means of a thermo junction in contact with it.

The author has designed an ammeter for this purpose made as follows. On two bracket supports (see Fig. 32) are carried a pair of brass T-pieces which are placed 5 or 7 cms. apart.

These T-pieces may be 4 or 5 cms. in length. To these are soldered a certain number of bare copper or platinoid wires, W, not larger than No. 40 S.W.G. size.

These wires must be spaced well apart. To the centre of one of these wires is attached a thermo-electric junction of copper and iron, J, or nickel and iron formed of very fine wires of these metals, not more than 0·05 mm. in diameter and not longer than 2 or 3 cms. The outer ends of these last fine wires are soldered to thick terminals,

T_1, T_2. The terminals are connected to a low resistance galvanometer, a very convenient form being a Paul single-pivot galvanometer having a resistance of not more than 4 or 5 ohms. When a high frequency current is sent through the fine copper wires these are heated. A thermo-electromotive force is created at the junction in contact with one of the hot wires and deflects the needle of the galvanometer in connection with it.

The ammeter can be calibrated by sending measured continuous currents through it, and observing the corresponding deflection of the thermocouple galvanometer. A curve is then delineated, showing the currents in terms of the corresponding deflections, which is parabolic in form. If then any oscillatory current is sent through the ammeter wires, and the deflection of the galvanometer needle is observed, a reference to the curve enables us to determine the root-mean-square value of these oscillations.

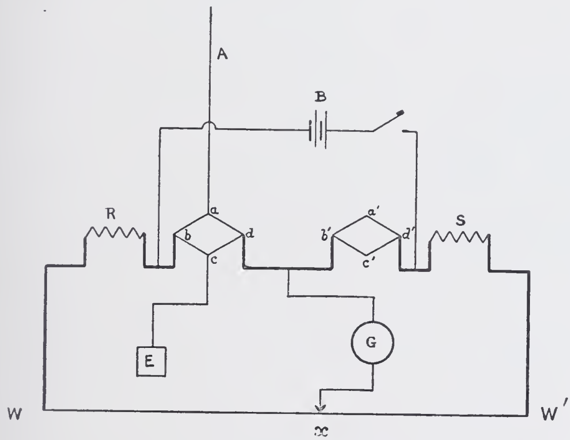


FIG. 33.—Bolometer Bridge.

Hot-wire ammeters of this kind are easily made and calibrated and very convenient for the measurement of electric oscillations damped or undamped.

12. The Bolometer-Bridge Method of measuring High Frequency Currents.—A third method of using a heated wire as an ammeter is the Bolometer-Bridge method. When a wire is traversed by electrical oscillations and is thereby heated, its resistance increases. This increase in resistance can be measured on a Wheatstone's bridge. By a separate experiment we can find the value of the steady continuous current, which equally heats the wire. For this purpose the wire to be heated by the oscillations, called the bolometer wire, must consist of a very fine iron or platinum wire, which must be arranged in a lozenge or diamond form (see Fig. 33). It is desirable to employ two equal circuits of the same sized wire. Let a, b, c, d and a', b', c', d' be these two circuits, and let them be joined with two other resistances, R and S, and with a battery and galvanometer, G, so as to form a Wheatstone's bridge. To two

opposite corners, *a*, *c*, of one of the diamond-shaped circuits are connected wires which lead into a circuit, in which oscillations are set up. These oscillations pass through the wires *a*, *b*, *c*, *d*, and heat them, but as the bridge connections are made to points at equal potential, *b* and *d*, there is no tendency for the oscillatory currents to stray into the bridge circuits. The balance of the bridge can thus be obtained both when the oscillations are flowing and when they are absent. The same circuit, *a*, *b*, *c*, *d*, can then be heated by a continuous current, so as to cause an equal increase in resistance, and the measurement of this equi-heating continuous current gives us the R.M.S. value of the electric oscillations.

A very sensitive bolometer bridge of the above type was employed by Professor C. Tissot, of the French Navy, in his admirable researches on resonance in antennæ.[60]

He employed as the bolometer wire extremely pure platinum wire freed entirely from iridium, so that it had as low a resistance and as high a temperature coefficient as possible.

By special purification he was able to obtain platinum having a temperature coefficient of 0·0032, increasing, therefore, 0·3 per cent. in resistance per degree centigrade with rise in temperature.

This platinum was drawn down into wire of extreme fineness by the Wollaston method, viz. by preparing a compound wire platinum inside with a sheath of silver outside, then drawing this down as fine as possible, and finally dissolving off the silver by nitric-acid.[61] In this manner he prepared platinum not more than 0·01 mm. in diameter.

Small rectangles were then made by attaching this wire to four terminals, and these were sealed up in an exhausted glass vessel. The sides of the rectangle were about 1·5 cm. in length, and had a resistance of about 17 ohms. These rectangles then were arranged as the two arms of a Wheatstone's bridge, as in Fig. 33, and one of the rectangles had its opposite corners connected respectively to the oscillatory circuit or to the antenna and earth-plate in which it was desired to measure the oscillatory current.

The sensibility of such a bolometer wire to current is greatly increased by placing the wire in a good vacuum, because the loss of heat from it by convection is greatly reduced, and therefore a given current raises its temperature higher and therefore increases by a larger percentage its resistance.

When combined with a properly arranged bridge and sensitive mirror galvanometer, such a bolometer wire is capable of indicating extremely small oscillatory currents. The bridge is first balanced so that the galvanometer needle remains at zero. The oscillations are then sent through one of the fine wire rectangles forming one arm of the bridge, it becomes heated, and the bridge balance is upset, and the needle deflects.

M. Tissot found that with one of his bolometers having a resistance of 42 ohms when used in the circuit of a receiving antenna

[60] See M. Camille Tissot, "Étude de la Résonance des Systèmes d'Antennes dans la télégraphic sans fils." Gauthier-Villars, Paris, 1906.

[61] For a number of useful references on this matter and information on the Wollaston process the reader is referred to the United States Patents, Nos. 767971 and 767981, granted to John Stone Stone, dated August 16, 1904.

he could measure the antenna current produced by a radiotelegraphic station 50 kilometres distant.

A bolometer bridge is therefore of great use in radiotelegraphic researches, because it enables us not merely to detect but to measure the mean-square value of the feeble oscillatory currents, whether damped or undamped, set up in a receiving antenna.

13. Electro-dynamic Current Indicators for High Frequency Currents. Fleming Alternating Current Galvanometer.—A form of alternating current galvanometer devised by the author in 1884 has of late years been found useful for the comparative measurement of high frequency currents. A copper or silver disc, R (see Fig. 34), is suspended by a very fine wire or bifilar suspension, so that it hangs within a coil, C, with the plane of the disc at 45° to the plane of the coil. If the coil is traversed by an alternating current, this creates induced currents in the disc, and it tends to set itself in a position with its plane more nearly parallel with the magnetic field of the latter.

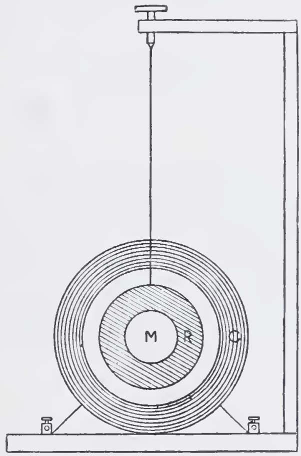


FIG. 34.—Electrodynamic Ammeter for Alternating Currents. (Fleming.)

The reason for this is because a closed conducting circuit having inductance when placed in an alternating magnetic field tends to set itself so as to decrease as much as possible the magnetic flux perforating through it. The proof of this will be found in an article on "Alternate Current Measurement," by Dr. W. E. Sumpner, in the *Proceedings of the Royal Society*, series A., vol. 80, p. 310, 1908.

The theory of this suspended disc dynamometer has been given in another form by Professor G. W. Pierce.[62] Let us assume that the disc is a ring of resistance, R, and inductance, L, and held in the centre of a coil of N turns, with its plane at an angle ϕ with that of the coil. Let M be the mutual inductance between the coil and ring. Let the coil be traversed by alternating currents of frequency $n = \frac{2\pi}{p}$, and let i_0 and i be the currents in the ring and coil respectively at any time, t. Then the torque F acting on the ring is $F = i_0 i \frac{dM}{d\phi}$.

The current in the coil is $i = I \sin pt$, and the E.M.F. induced in the ring is—

$$e_0 = \frac{d}{dt}(-iM) = -M\frac{di}{dt} - i\frac{dM}{dt}$$

For small deflections $\frac{dM}{dt} = 0$, and we have—

$$e_0 = -MIp \cos pt$$

[62] See Prof. G. W. Pierce, "On Resonance in Wireless Telegraph Circuits," *Physical Review*, April, 1905, vol. xx. p. 226.

The equation for the current in the ring is therefore—

$$L\frac{di_0}{dt} + Ri_0 = - MIp \cos pt$$

$$\text{Hence} \quad i_0 = \frac{-MIp(\cos pt - \theta)}{\sqrt{R^2 + p^2L^2}}$$

where $\theta = \tan^{-1}\frac{Lp}{R}$.

Accordingly, we have for the torque at any instant—

$$F = \frac{-MI^2p \sin pt \cos (pt - \theta)}{\sqrt{R^2 + p^2L^2}}$$

The average value of this is—

$$\bar{F} = \frac{1}{T}\int_o^T Fdt = -\frac{LMp^2I^2}{2(R^2 + p^2L^2}\cdot\frac{dM}{d\phi}$$

Maxwell has given an expression for the mutual induction of two circles, whose planes make an angle ϕ with each other.[63] From this expression it is found that if the centres of the circles coincide, and their planes make an angle of 45°, we have $\frac{M}{2}\cdot\frac{dM}{d\phi} = \frac{\pi^4r^4r_0^{\ 4}}{D^6}$. Hence, if there are N turns in the coil, we have finally as the expression for the average torque acting on the ring—

$$\bar{F} = \frac{LN^2p^2I^2}{R^2 + p^2L^2}\cdot\frac{\pi^4r^4r_0^{\ 4}}{D^6}$$

where r and r_0 are the radii of the circular fixed coil and suspended ring respectively, and D is the distance from the centre of the ring to the perimeter of the fixed coil. The less value D can have is, therefore, r, which happens when the centres of ring and coil coincide.

The average torque on the ring, and therefore its deflecting moment, is proportional to the square of the current in the coil and proportional to the square of the frequency for the same instrument. If, therefore, the frequency is constant, and if the ring is suspended by a fine wire or quartz fibre so that the restoring torque varies as the deflection nearly, the deflection will measure the mean-square value of the current passing through the coils. Professor G. W. Pierce has confirmed this conclusion experimentally.

With certain precautions, therefore, the instrument may be used to measure the mean-square value of trains of electric oscillations.

If it is desired to construct an instrument which shall act merely as an indicator of alternating current, but not of an ammeter, we may suspend within a coil a small needle of soft iron by a quartz fibre or bifilar suspension. The iron needle should be placed with its axis at 45° to the plane of the coil. When alternating currents or oscillations are passed through the coil, the needle will deflect, and its deflections may be rendered evident by attaching to it a small mirror as usual.

If high frequency oscillations are to be detected, the needle must not be a thick solid piece of iron, but must be a small bundle of

[63] See Maxwell's "Electricity and Magnetism," vol. ii. p. 308.

extremely fine iron wires, each one of which is insulated from the rest by shellac varnish.

14. High Frequency Potential Measurements.—We are concerned in making two distinct potential measurements in connection with high frequency currents. First, we may require the maximum value of the potential difference of two points on a circuit when it is traversed by electric oscillations; or, second, we may wish to know the root-mean-square value of the oscillation between the same points. The measurement of the maximum potential is best made by observations on the length of spark which such potential difference will create between metallic balls of equal and known diameter. We have already given tables of the dielectric strength of air for various spark lengths and spark-ball sizes. We may for most practical purposes determine the maximum value of the potential difference between two

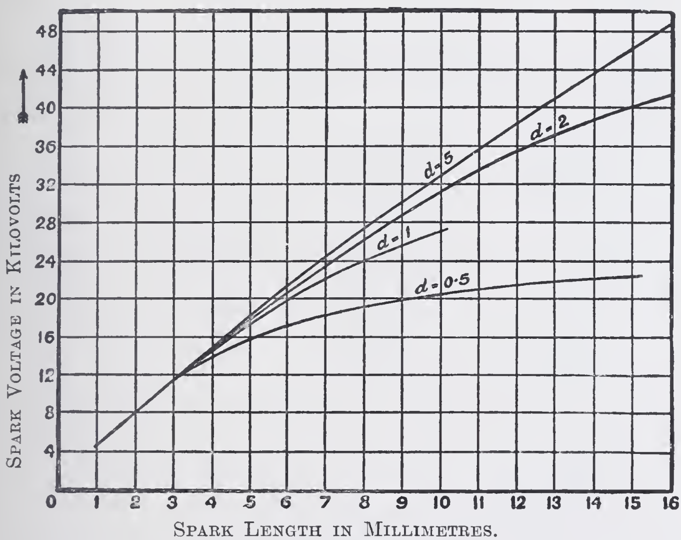


Fig. 35.—Spark Voltages for Various Spark Lengths and Spark Balls of Various Diameters, *d* cms.

places which exceeds 4000 volts or so by attaching to these points the terminals of a spark-ball discharger, the distance between the balls being measurable by a screw with divided head. These balls should be clean brass balls of 1 or 2 cms. in diameter, so that we may avail ourselves of the numerous observations which have been made on the sparking potential for various distances between such surfaces. The curves in Fig. 35 are plotted from the figures of observations taken by A. Heydweiller (see *Wied. Ann.*, 1893, vol. 48, p. 234), and give by inspection the voltage between spark balls varying in diameter from 0·5 cm. up to 5 cms. or 2 inches.

It will be seen that the smaller the ball the more has the curve a tendency to bend over so as to become parallel to the axis of spark length. Hence there is an advantage in the use of large spark balls

for obtaining high charging potentials for condensers, since the spark voltage for a given spark length increases within a certain limit with the diameter of the balls.

The following table gives the results of Heydweiller's observations on spark voltages between balls of various diameters and for spark lengths between 1 and 16 mm., which are graphically depicted in Fig. 35 :—

TABLE SHOWING THE MEASUREMENT OF SPARK VOLTAGES FOR VARIOUS LENGTHS OF SPARK TAKEN BETWEEN SPARK BALLS OF VARIOUS DIAMETER AT NORMAL ATMOSPHERIC PRESSURE AND TEMPERATURE BY HEYDWEILLER.

v = spark voltage.
d = spark-ball diameter in centimetres.
l = spark length in millimetres.

$d = 5{\cdot}0$ cms.		$d = 2{\cdot}0$ cms.		$d = 1{\cdot}0$ cm.		$d = 0{\cdot}5$ cm.	
l in millimetres.	v in volts.	l in millimetres.	v in volts.	l in millimetres.	v in volts.	l in millimetres.	v in volts.
5	18,360	1	4,710	1	4,800	1	4,830
6	21,600	2	8,100	2	8,370	2	8,370
7	24,540	3	11,370	3	11,370	3	11,340
8	27,330	4	14,490	4	14,550	4	13,770
9	30,090	5	17,490	5	17.310	5	15,720
10	32,850	6	20,370	6	19,920	6	17,190
11	35,580	7	23,250	7	22,050	7	18,300
12	38,310	8	26,040	8	24,090	8	19,020
13	41,010	10	31,290	9	25,590	10	20,190
14	43,680	12	35,490	10	27,000	15	22,320
15	46,230	14	38,640				
16	48,660	16	41,280				

The Table on p. 205 gives the spark voltages for various spark lengths taken between balls 2 cms. in diameter. The figures up to 1·5 cm. are taken from Heydweiller's observations, and those beyond from observations by J. Algermissen and given on the authority of Dr. J. Zenneck (see "Elektromagnetische Schwingungen und Drahtlose Telegraphie," by Dr. J. Zenneck, Stuttgart, 1905).

These tables provide the means for obtaining the spark voltage from the measurement of the spark length between metallic balls 2 cms. in diameter, but must not be applied in the case of balls much larger or smaller.

Baille and Paschen have also made experiments on the spark voltage for different lengths of spark between metal balls of various diameters in air at atmospheric pressure and temperature,[64] and have shown that the spark potential varies considerably with the size of the balls, and some of their results are given in the Table on p. 206, and graphically in Fig. 36. From Heydweiller's observations, as well as those of Baille and Paschen, it will be seen that up to a spark length of 4 mm. the variation in the diameter of spark balls between 0·5 cm.

[64] See Baille, *Annales de Chemie de la Physique* (5), 1882, vol. 25, p. 486.

TABLE SHOWING THE SPARK VOLTAGE BETWEEN BRASS BALLS, 2 CMS. IN DIAMETER, FOR VARIOUS SPARK LENGTHS.

Spark length in centimetres.	Spark voltage.	Spark length in centimetres.	Spark voltage.
0·1	4,700	2·7	54,900
0·2	8,100	2·8	55,800
0·3	11,400	2·9	56,700
0·4	14,500	3·0	57,500
0·5	17,500	3·1	58,300
0·6	20,400	3·2	59,000
0·7	23,250	3·3	59,700
0·8	26,100	3·4	60,400
0·9	28,800	3·5	61,100
1·0	31,300	3·6	61,800
1·1	33,300	3·7	62,400
1·2	35,500	3·8	63,000
1·3	37,200	3·9	63,600
1·4	38,700	4·0	64,200
1·5	40,300	4·1	64,800
1·6	41,300	4·2	65,400
1·7	43,200	4·3	66,000
1·8	44,700	4·4	66,600
1·9	46,100	4·5	67,200
2·0	47,400	4·6	67,800
2·1	48,600	4·7	68,300
2·2	49,800	4·8	68,800
2·3	51,000	4·9	69,300
2·4	52,000	5·0	69,800
2·5	53,000	5·1	70,300
2·6	54,000		

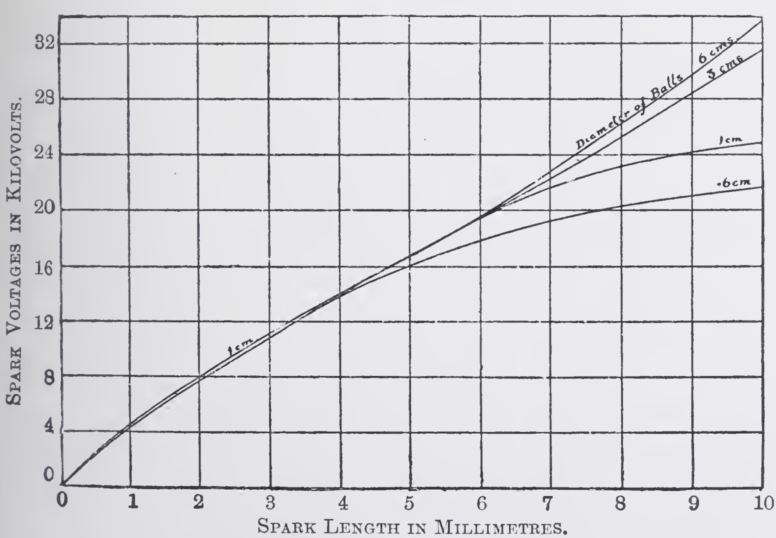


FIG. 36.—Curves showing Spark Voltages in Kilovolts for Various Spark Lengths in Millimetres. (Baille and Paschen.)

and 6 cms. makes but little variation in the spark potential, but beyond this length the spark voltage for a given spark length rises very rapidly.

TABLE SHOWING THE MEASUREMENT OF SPARK VOLTAGE FOR VARIOUS SPARK LENGTHS AND SPARK-BALL DIAMETERS IN AIR AT NORMAL PRESSURE, BY BAILLE AND PASCHEN.

Spark length in centimetres.	Spark voltage for balls of diameter.			
	6 cms.	3 cms.	1 cm.	0·6 cm.
0·1	4,434	4,500	4,575	4,660
0·2	7,680	7,800	8,040	8,050
0·3	10,840	10,980	11,200	11,200
0·4	13,900	14,030	14,290	13,902
0·5	16,500	16,500	16,400	15,975
0·6	19,570	19,570	19,570	17,900
0·7	22,620	22,140	21,680	19,266
0·8	26,400	25,430	23,280	20,325
0·9	29,230	28,390	24,000	21,180
1·0	33,900	31,410	24,900	21,714

It is clear on comparing all the results given for spark voltage that there are very sensible differences between the results given by various observers for the spark voltage for given lengths of spark even between balls of the same diameter.

As the voltage required to produce a spark of given length in air at ordinary pressure between metal balls is an important number, we shall collect here the results for sparks between 1 and 6 mm. in length as given by various observers.

MM. Bichat and Blondlot have measured spark voltages for various lengths of sparks in air at normal pressure taken between metal balls 1 cm. in diameter.

The observations made by R. Gray on dielectric strength of air (*loc. cit.*) between metal surfaces, which were parts of spheres 70 cms. in diameter, have been reduced to spark voltages for the stated spark lengths. Also those by T. W. Edmondson (*loc. cit.*) between balls 3 cms. in diameter, and observations made in the Physical Laboratory of University College, London, with spark balls 2·6 cms. in diameter. These spark voltages for various spark lengths from 1 to 6 mm. are set out below, and the mean of all the results is given in the last column.

Spark length in air.	Spark voltage according to observations of—				Mean results.
	Bichat and Blondlot.	T. Gray.	T. W. Edmondson.	University College.	
1 mm.	4,765	4,360	4,069	5,151	4,586
2 ,,	8,140	7,560	7,812	8,181	7,924
3 ,,	11,307	10,830	11,400	11,300	11,210
4 ,,	14,119	13,800	15,000	14,361	14,320
5 ,,	16,664	16,800	18,630	17,421	17,380
6 ,,	19,210	19,620	22,290	20,481	20,400

Heydweiller (*loc. cit.*) gives a table of collected results of spark voltages for different spark lengths between balls 0·5 cm. in diameter. He quotes from the following memoirs :—

Czermak, *Wien Ber.* (2), 1888, vol. 97, p. 307.
Freyberg, *Wied. Ann.*, 1889, vol. 38, p. 250.
Paschen, *Wied. Ann.*, 1889, vol. 37, p. 69.
Baille, *Ann. Chim. et Phys.* (5), 1882, vol. 25, p. 486.
Bichat and Blondlot, *Jour. de Phys.* (2), 1886, vol. 5, p. 457.
Obermayer, *Wien Ber.* (2), 1889, vol. 100, p. 134.
Quincke, *Wied. Ann.*, 1883, vol. 19, p. 545.

For additional information we must refer the reader to these papers, also to an important paper by Dr. A. Russell "On the Dielectric Strength of Air" (*Proc. Phys. Soc. Lond.*, November, 1905), to which reference has already been made.

The results of observations by various observers who have measured the spark voltage required to produce a spark in air at normal pressure 1 mm. in length are also given below :—

Observer.	Spark voltage to produce 1 mm. spark in air at normal pressure.	Spark surfaces.
Lord Kelvin	4000 volts	Slightly curved metal plates.
Mascart	5490 ,,	Metal balls, 22 mm. diameter.
De la Rue and H. Miller	4330 ,,	Metal discs.
Bichat and Blondlot	4765 ,,	Metal balls, 10 mm. diameter.
T. Gray	4360 ,,	,, ,, 70 cms. ,,
T. W. Edmondson	4069 ,,	,, ,, 3 ,, ,,
Observations at University College, London	5151 ,,	,, ,, 2·6 ,, ,,

Mean value = 4597, say 4600 volts.

Hence we are not far wrong in accepting 4600 volts as the approximate value of the electromotive force required to produce a spark 1 mm. in length between metal balls about 1 inch in diameter in air at normal pressure and temperature.

It should be noted, however, that as the balls get hot by sparks passing, the spark voltage for a given length decreases. Hence the above figures apply only to cool balls. Moreover, ultra-violet light falling on the balls will greatly decrease the spark voltage for a given length, therefore in all such measurements the spark micrometer balls must be carefully protected from the light of other sparks or electric arcs.

The above figures enable us to tell approximately the potential to which a condenser such as a Leyden jar is charged when it yields a spark discharge of any length between 0 and 5 cms.

The second kind of potential measurement which has to be made is that of the root-mean-square or effective value. This is accomplished by means of an electrostatic voltmeter in which the "needle" is connected to one pair or set of quadrants. Since the attraction between the fixed and movable parts varies as the square of their potential difference, the deflection of an electrostatic voltmeter connected as above mentioned measures the root-mean-square (R.M.S.) value of the potential difference of its own quadrants.

Hence if we have an oscillatory circuit containing a spark gap,

and apply to the terminals of the condenser or to the spark balls an electrostatic voltmeter, we can find from the spark length the maximum voltage V, and from the voltmeter reading the mean-square-voltage, and if we measure also the capacity and inductance in the circuit, we have at once the means of calculating the frequency n, and therefore the logarithmic decrement of the oscillations, as we shall show in the next chapter (see Chap. III.).

15. Measurement of Spark Frequency.—Another measurement frequently required is that of spark frequency. If an induction coil or transformer is connected to a pair of spark balls which are short-circuited by an inductance and condenser in series with one another, then oscillatory sparks pass between the balls when the potential reaches a value corresponding to the spark length. It is impossible to calculate the power being given to the condenser circuit unless we know how many of these trains of oscillations, that is, how many oscillatory sparks take place per second. It is not possible to count these sparks, because they may come at the rate of even 50 or 100 per second. Neither can we assume that the number of sparks is equal to the number of interruptions of the primary circuit of the induction coil or the number of alternations of the alternating circuit if a transformer is being employed. The number of sparks per second may be less or more according to circumstances. Thus, for instance, if an alternating current is being employed having a frequency of 50, it will depend upon the inductance and the capacity in the oscillating circuit, and upon the inductance inserted between the secondary circuit of the transformer and the spark balls, whether we have a number of sparks per second greater than, equal to, or less than the number of alternations per second with the alternating current supplying the transformer. The author has therefore devised the following appliances for measuring spark frequency.

A well-made wooden box, perfectly light-tight and blackened in the interior with a door on one side, is furnished with a good rapid rectilinear camera lens, L, at one side. The lens tube has the usual iris diaphragm. The box is 38 cms. high, 38 cms. wide, and 25 cms. broad. The lens tube is prolonged by another tube closed at the end but with a very small hole, H, in the cover. In the interior of the box is a train of clockwork, W, which drives round a vertical shaft about 18 times per minute (see Fig. 37). This shaft carries a cubical block of aluminium, M, to the four sides of which are affixed carefully flatted glass plates silvered on the surface. This cubical mirror is so placed that it receives a ray passing through the small hole in the collimator tube, and gathered by the lens, and reflects it at right angles, or nearly so, so that the ray falls on a slit, S, in the side of the box, about 1 cm. wide and 7 or 8 cms. in length. Outside the box, a plate carrier, P, slides down in grooves in such fashion, that when the slide is drawn out the exposed sensitive plate glides past the slit in the box. The same clockwork that drives round the cubical mirror lowers the photographic plate at a uniform rate so that it travels over the slit.

If, then, the pinhole in the end of the collimator is illuminated intermittently by the image of a spark thrown on it, then the ray passing through the lens and reflected from the revolving mirror is brought to a focus on the photographic plate and sweeps across it,

imprinting an image on the plate at intervals depending on the frequency of the spark. Four times in each revolution of the block M

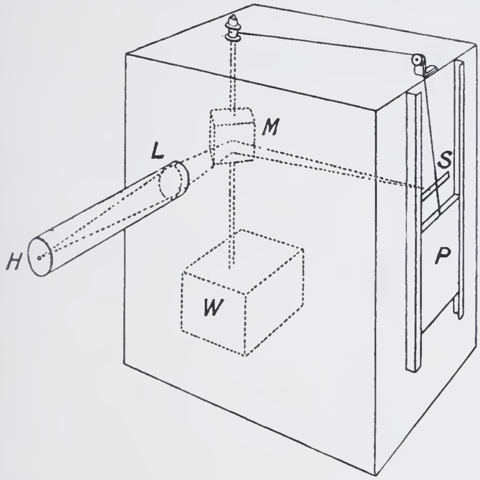
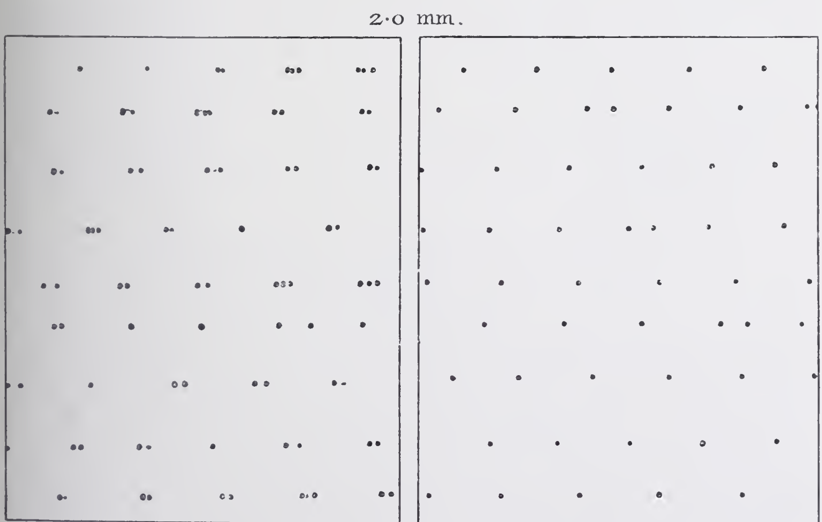


Fig. 37.—Photographic Spark Counter. (Fleming.)

a train of images sweeps over the gradually falling photographic plate, and when this is developed we find it covered with rows of black spots, each of which denotes the occurrence of a spark (see



(a) (b)

Fig. 38.—Records of Photographic Spark Counter.

Fig. 38 (b)). It is clear that the number of sparks per second bears a definite relation to the speed of revolution of the mirror and to the

angle subtended by the slit at the mirror, and to the speed at which the photographic plate is lowered past the slit in the camera.

It is convenient to have a mark on the photographic plate carrier, and a scale at the side to determine the time T taken by the plate to move down, say, 10 cms.

Let l be the length of this slit, which in the camera designed by the author is 7·9 cms., and let θ be the angle in degrees which this slit subtends at the mirror surface. Then $\frac{\theta}{360}$ is the fraction of one complete revolution which the reflected ray turns through in sweeping over a slit of length l.

If the photographic plate descends a distance d cms. per revolution of the mirror block, and takes a time T seconds to descend a distance D cms., then the time taken by the mirror to turn through one revolution is $\frac{\mathrm{T}d}{\mathrm{D}}$ and to turn through 1° is $\frac{\mathrm{T}d}{360\mathrm{D}}$, and to turn through an angle θ is $\frac{\mathrm{T}d\theta}{360\mathrm{D}}$. Hence half this time, or $\frac{1}{2}\,\frac{\mathrm{T}d\theta}{360\mathrm{D}}$, is the time taken for the ray to sweep over the slit of length l. Hence the time interval t corresponding to a length of 1 cm. on the photographic plate is $t = \frac{\mathrm{T}d\theta}{l\mathrm{D}720}$ seconds $= \mathrm{CT}$. If, then, there are N spark images on the plate in M rows, the average number per row is $\frac{\mathrm{N}}{\mathrm{M}}$, and the average space interval in cms. between images is $\frac{\mathrm{WM}}{\mathrm{N}}$ where W is the width of the plate in cms. Therefore $\frac{\mathrm{WMCT}}{\mathrm{N}}$ is the average time interval in seconds between the sparks, or $\frac{\mathrm{N}}{\mathrm{MWCT}}$ is the spark frequency.

In the spark counter constructed by the author, the constant C is equal to 0·00102, or very nearly $\frac{1}{1000}$, and the spark frequency n is given by the formula—

$$n = \frac{\text{Total number of spark images on plate}}{\text{number of rows of images} \times 0{\cdot}00102\ \mathrm{T} \times 7{\cdot}9}$$
$$= \frac{1000}{8\mathrm{T}} \times \frac{\text{Number of spark images on plate}}{\text{number of rows of images}}$$

The formula is checked by the following device. On the shaft of an electric motor is placed a sheet tin disc 2 feet in diameter having four holes an inch in diameter near the edge at quadrantal positions. Behind the disc is placed a small arc lamp, so that the light shines through these holes. When the motor is set in revolution with a speed of 3000 R.M.P., and its speed carefully determined with a tachometer, we have flashes of light emitted by the arc through the holes at the rate of about 200 per second. If we treat these flashes as if they were sparks and photograph them with the spark counter, we then find, on developing the plate, a number of black dots, which are the images of the collimator hole intermittently illuminated by the flashes coming at a known rate per second. On applying the

formula given above to calculate the number of flashes from the number of images, we find an agreement with the actual number within 1 per cent. Such a control plate gives us, therefore, the means of confirming the accuracy of the formula and testing the photographic counter.

When such a spark counter is used to photograph the oscillatory spark at the spark balls of a radiotelegraphic transmitter, we find that the results are extraordinarily different according to the nature of the potential generator used, whether induction coil or transformer —also on the nature of the interrupter if a coil is used, and especially upon the length of the spark gap, and whether it has an air blast applied to it or not.

We shall consider in a later chapter (VIII.) some of the information which can be obtained by the aid of this spark counter.

CHAPTER III

DAMPING AND RESONANCE

1. The Logarithmic Decrement of Electric Oscillations and the Damping.—We have seen that when electric oscillations are excited in a circuit having resistance, inductance, and capacity, by permitting a sudden discharge to take place across a spark gap in it, we have produced in the circuit high frequency alternating currents which continually decay in amplitude, thus constituting a train of *damped oscillations*.

This decay may arise from several causes, acting singly or together, but is essentially dependent upon some action which dissipates the initial energy imparted to the condenser.

We shall consider first the simplest case.

Let the circuit be a closed inductive circuit of constant resistance, the capacity in it consisting of a condenser, the plates of which are very near together. Also let the capacity and inductance have such values that the periodic time of a free oscillation in the circuit is large, compared with the time taken by an electric impulse to travel round the circuit. Since this velocity is the same as the velocity of light, the above condition is fulfilled when the length of the circuit does not exceed a few metres, and the natural periodic time is something of the order of a millionth of a second. Under the above circumstances the method of investigation applied in Chap. I., § 5, to the discharge of a condenser is valid. This is the case for most oscillatory circuits likely to be employed in practice. Then let C be the capacity in the circuit, L the inductance, and R′ the high frequency resistance of the circuit employed.

The inductance and capacity can be measured or calculated, and the frequency is then very approximately determined by the expression—

$$n = \frac{1}{2\pi\sqrt{CL}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

In this equation C and L must both be measured in consistent units—that is, in farads and henrys, or both in electro-magnetic units. If C is measured in microfarads and L in centimetres, then, as already shown—

$$n = \frac{5 \times 10^6}{\sqrt{CL}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

It is convenient to measure C and L in these last-named units in practice.

The quantity $\sqrt{\mathrm{CL}}$ is then called the *oscillation constant* of the circuit, and varies inversely as the frequency, for—

$$\sqrt{\mathrm{CL}} = \frac{5 \times 10^6}{n}$$

Thus, if the oscillation constant has a value, say, 10, this means that the product of the numbers representing the capacity reckoned in microfarads and the inductance in centimetres is 100.

If we denote the current in the circuit at any instant by i, then it has been shown in Chap. I., § 2, that we may express i as a function of the time by the equation—

$$i = \mathrm{I}\epsilon^{-at} \sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where a stands for $\frac{\mathrm{R}'}{2\mathrm{L}}$ and I is some constant.

If in this equation we put successively, as on page 4—

$$t = \frac{\phi}{\pi}\frac{T}{2}, \quad t = \frac{\phi}{\pi}\frac{T}{2} + \frac{T}{2}, \quad t = \frac{\phi}{\pi}\frac{T}{2} + T, \text{ etc.}$$

we obtain the values of the successive maximum currents, I_1, I_2, I_3, etc., in opposite directions, where $\phi = \tan^{-1} p/a$.

If we take the ratios of these successive maxima, we have—

$$\frac{\mathrm{I}_1}{\mathrm{I}_2} = \frac{\mathrm{I}_2}{\mathrm{I}_3} = \frac{\mathrm{I}_3}{\mathrm{I}_4}, \text{ etc.} = \epsilon^{\frac{aT}{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The quantity a is called the *damping factor*, and $\frac{aT}{2} = \frac{a}{2n} = \frac{\mathrm{R}'}{4n\mathrm{L}}$ is denoted by δ, and is called the *logarithmic decrement of the oscillations per half period.* Accordingly—

$$\frac{\mathrm{I}_1}{\mathrm{I}_2} = \frac{\mathrm{I}_2}{\mathrm{I}_3} = \frac{\mathrm{I}_3}{\mathrm{I}_4}, \text{ etc.} = \epsilon^{\delta}$$

$$\text{or} \quad \delta = \log_\epsilon \frac{\mathrm{I}_1}{\mathrm{I}_2} = \log_\epsilon \frac{\mathrm{I}_2}{\mathrm{I}_3}, \text{ etc.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The damping factor a is a quantity the *dimensions* of which are those of the reciprocal of a *time*, whilst the logarithmic decrement is a mere numeric.

The logarithmic decrement is here defined to be the Napierian logarithm of the ratio of two successive maximum currents or oscillations in *opposite* directions. Most German physicists, following the example of Bjerknes, define the decrement to be the logarithm of the ratio of two successive maximum oscillations in the *same* direction; that is, separated by an interval of one period, instead of one half-period. In interpreting formulæ in which a symbol for the decrement occurs, it is necessary to notice whether the writer takes the decrement to be defined as the natural logarithm of two successive oscillations in the same or in opposite directions, since the decrement in the former case is double that in the latter.

The quantity $\epsilon^{-\delta}$ is called *the damping* of the oscillations, and is the ratio of one maximum to the one preceding it in the opposite direction.

If the circuit contains no spark gap, and is a nearly closed or

non-radiative circuit, the logarithmic decrement is a constant determined by the capacity, inductance, and resistance of the circuit.

The successive maximum values of the currents, or potential differences of any two points, decrease in accordance with an exponential law, and the logarithmic decrement can be calculated at once, when we know the inductance, resistance, and capacity in the circuit.

For since $\delta = \frac{R'}{4nL}$, and since $n = \frac{1}{2\pi\sqrt{CL}}$, we have the value of the logarithmic decrement for the closed non-radiative circuit given by the expression—

$$\delta = \frac{\pi}{2} R' \frac{\sqrt{C}}{\sqrt{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The value of the high frequency resistance R′ can be calculated from the ordinary or ohmic resistance by the formulæ already given (see Chap. II., § 1), when we know the frequency, provided the wire is approximately straight or bent into a curve of large radius.

The cases, however, in which we can apply the above expression (6) are not numerous, since most nearly closed oscillatory circuits for which we wish to know the decrement contain a spark gap, the resistance of which is not constant, or else are wound in spirals, and in addition we have in the case of all open circuits a loss of energy due to electro-magnetic radiation, producing a damping of the oscillations far exceeding that due to true resistance alone.

Furthermore, it must be noticed that when two circuits are coupled together inductively the establishment of an electric oscillation in one circuit creates an induced oscillation in the other. Hence, even if the secondary circuit is a closed non-radiative circuit without spark gap, its logarithmic decrement is increased by the mere fact of the proximity of the primary circuit, on which the secondary circuit exercises a reciprocal inductive action.

2. The Mean-square and Root-mean-square Value of a Train of Oscillations.—Let i denote the current in a circuit at any time, t, after the commencement of a train of oscillations in it having a frequency n. Let δ stand for the logarithmic decrement per semi-period. Then, assuming that δ is a small quantity in comparison with π, it follows from equation (4) of Chap. I. that the current can be expressed as a function of the time in the form—

$$i = I_1 \epsilon^{\delta/2} \epsilon^{-at} \sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

In this expression I_1 stands for the first maximum value of the oscillations which occurs at a time $t = \frac{T}{4}$ reckoned from initial zero.

If we square equation (7) we obtain—

$$i^2 = I_1^2 \epsilon^{\delta} \epsilon^{-2at} \sin^2 pt \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

which gives us an expression for the square of the instantaneous value of the current. Suppose that an electric oscillation is passed through a very thin wire or electrolytic conductor, of which the high frequency resistance is the same as its steady or ohmic resistance, R,

then the rate at which heat is generated at any instant is given by the expression—

$$\mathrm{R}i^2 = \mathrm{R}I_1^2\epsilon^{\delta}\epsilon^{-2\alpha t}\sin^2 pt \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

We cannot easily measure the instantaneous rate of evolution of heat, but if we allow a series of trains of oscillations at the rate of N per second to pass through the conductor, there will be a certain steady rate of production of heat, which is measured by the mean value of the quantity $\mathrm{R}i^2$, taken at numerous equidistant intervals during the second.

It is important, therefore, to determine an expression for the mean value of the square of the currents forming a train of electric oscillations.

The mean value of the square of the currents taken at equidistant intervals of time during an oscillation is called the *mean-square value* of the current (M.S. value).

The *mean-square* (M.S.) value of the oscillations when multiplied by the effective resistance of the circuit gives us the average rate of production of heat in the circuit or the dissipation of energy in it.

If there are N of these trains of oscillations per second, then, since each oscillation is completed in a small fraction of a second, we can say that the mean value of the square of i during one second of time is given by the integral—

$$\mathrm{J}^2 = \mathrm{N}\int_0^\infty i^2 dt^{(1)}$$

Hence, to obtain this mean-square current we have to find the value of the integral—

$$\int_0^\infty \epsilon^{-2\alpha t}\sin^2 pt \,.\, dt = \int_0^\infty \epsilon^{-2\alpha t}\left(\frac{1-\cos 2pt}{2}\right)dt$$

$$\text{or of} \quad \int_0^\infty \tfrac{1}{2}\epsilon^{-2\alpha t}dt - \int_0^\infty \tfrac{1}{2}\epsilon^{-2\alpha t}\cos 2pt \,.\, dt$$

A reference to any treatise on the integral calculus will show that—

$$\int \epsilon^{nx}\cos mx \,.\, dx = \epsilon^{nx}\left(\frac{n\cos mx + m\sin mx}{m^2+n^2}\right)$$

Hence we have—

$$\int \epsilon^{-2\alpha t}\cos 2pt \,.\, dt = \epsilon^{-2\alpha t}\left(\frac{2p\sin 2pt - 2\alpha\cos 2pt}{4(\alpha^2+p^2)}\right)$$

If, therefore, we denote by J the *root-mean-square value* [2] (R.M.S. value) of the N groups of oscillations per second, so that J is defined by the integral—

$$\mathrm{J} = \sqrt{\mathrm{N}\int_0^\infty i^2\,dt}$$

[1] By German writers the mean-square value of the current, or the value of the integral J^2, is generally called the *integral value* of the oscillations or of the oscillation train.

[2] The expression *root-mean-square value* (R.M.S. value) is an abbreviation for the long expression, "the value of the square root of the mean of the squares of the currents or electromotive forces taken at numerous equidistant intervals of time throughout a single period, or of the time of a train of oscillations."

and if i denotes the current at any time, t, such that—

$$i = I_1\epsilon^{\delta/2}\epsilon^{-at}\sin pt$$

we have—

$$J^2 = NI_1^2\epsilon^{\delta}\int_0^{\infty}\epsilon^{-2at}\sin^2 pt \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Substituting in (10) the proper value of the definite integral as given above, we have—

$$J^2 = NI_1^2\epsilon^{\delta}\frac{p^2}{4a(a^2+p^2)}$$

now $p = 2\pi n$ and $a = 2n\delta$, hence—

$$\frac{p^2}{a^2+p^2} = \frac{1}{1+\left(\frac{\delta}{\pi}\right)^2}$$

$$\text{and} \quad J^2 = \frac{NI_1^2\epsilon^{\delta}}{8n\delta}\cdot\frac{1}{1+\left(\frac{\delta}{\pi}\right)^2}$$

In all practical cases $\frac{\delta}{\pi}$ is a quantity not greater than 0·1, and often as small as 0·01. Hence, in those cases in which $\frac{\delta^2}{\pi^2}$ is small compared with unity, we can say that the mean-square value of the oscillations having N trains per second is given by—

$$J^2 = \frac{NI_1^2\epsilon^{\delta}}{8n\delta} = \frac{NI_1^2\epsilon^{\delta}}{4a}$$

If the oscillations are not strongly damped, which is the case for a nearly closed oscillatory circuit when the high frequency resistance R' is small compared with $4nL$ for that circuit, then the quantity ϵ^{δ} is nearly unity, and the value of the mean-square current J^2 for N trains of oscillations per second is—

$$J^2 = \frac{NI_1^2}{4a}$$

$$\text{Hence} \quad J = \sqrt{\frac{N}{4a}}\cdot I_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

The root-mean-square current J is therefore proportional to the first maximum value of the oscillations, and to a factor which depends upon the number of trains of oscillations per second and the damping factor of each train.

It has been already shown (see Chap. I., § 5, equation 17) that if a condenser of capacity C is charged to a potential V, and then discharged through an inductive circuit, the current i at any time, t, reckoned from the instant when the discharge commences, is given by the expression—

$$i = CpV\epsilon^{-at}\sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Comparing together equations (10) and (12), we see that—

$$CpV = I_1\epsilon^{\delta/2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Hence, substituting in equation (11), we have—

$$J^2 = \frac{NC^2p^2V^2}{8n\delta}$$

If the capacity C and inductance L are measured in absolute measure, then $p^2 = \frac{1}{CL}$, and therefore—

$$J^2 = \frac{\pi NV^2C\sqrt{C}}{4\delta\sqrt{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

from which we have—

$$\delta = \frac{\pi NV^2C\sqrt{C}}{4J^2\sqrt{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

If the above equation (15) is compared with (6), it will be seen that they differ only in that the quantity R′ in the latter is replaced by the quantity $\frac{NV^2C}{2J^2}$ in the former. The energy stored in the condenser at each charge is measured by $\frac{1}{2}CV^2$, and if there are N discharges per second, which all expend themselves in heating the circuit, having high frequency resistance R′, the R.M.S. value of the current being J, we must obviously have the equation $R'J^2 = \frac{1}{2}NCV^2$. Hence (15) can be deduced from (6) merely by the application of the principle of conservation of energy.

3. Determination of the Number of Oscillations by the aid of the Decrement.—A knowledge of the value of the logarithmic decrement of the oscillations taking place in any circuit enables us to calculate the number of oscillations of current or potential which take place before their maximum value is reduced in any assigned ratio and the oscillations practically extinguished. If we consider the decrement to be constant, and I_1 to denote the first maximum oscillation and I_m the mth, then—

$$\frac{I_1}{I_m} = \epsilon^{(m-1)\delta} \quad . \quad . \quad . \quad . \quad (16)$$

$$\text{Hence} \quad \log_\epsilon \frac{I_1}{I_m} = (m-1)\delta \quad . \quad . \quad . \quad . \quad (17)$$

and from this last equation (17) we can determine m when we have selected any desired ratio for $\frac{I_1}{I_m}$. Thus, let us suppose that the oscillations are to be considered as extinguished for all practical purposes when $\frac{I_1}{I_m} = 100$, that is, when the last is only 1 per cent. of the first. We have then—

$$m = \frac{4{\cdot}605 + \delta}{\delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Thus if $\delta = 0{\cdot}015$ we have $m = 305$.

This gives us the number of *semi-oscillations* which elapse before the maximum value of the oscillation is reduced to 1 per cent. of its initial or first maximum value. In this case, therefore, 150 *complete oscillations* would constitute the wave train for all practical purposes.

On the other hand, if $\delta = 0{\cdot}4$ we find that $m = 12{\cdot}5$, and not more than half a dozen complete oscillations would then take place before the oscillation train had subsided.

In any case, therefore, where we have the means of counting the actual number of oscillations which take place, we can assign an approximate value to the logarithmic decrement. Conversely, if we find such a value as 0·3 or 0·4 for the decrement, we know that it means that the oscillations are extinguished after about half a dozen periods; whereas if the decrement is as low as 0·02 or 0·01, we infer that some hundreds of complete oscillations constitute a train. In some circuits as many as 1000 complete oscillations may take place in a single group, and in others hardly more than two or three, if an impulsive electromotive force is applied and the circuit then left to itself.

4. Practical Determination of the Logarithmic Decrement of Electric Oscillations.—It will be seen from the previous sections that the practical determination of the logarithmic decrement for any oscillatory circuit and for certain types of circuit is an important matter, since the physical effects which arise in many cases depend in large degree upon the duration of the train of oscillations or number of complete oscillations in a group or wave train.

The majority of oscillating circuits for which we desire to predetermine the logarithmic decrements, have a spark gap in them.

It has been shown by Dr. J. Zenneck[3] that when an oscillating circuit contains a spark gap the simple exponential law of decay no longer holds good, and the logarithm of the ratio of successive maxima is no longer constant. The decadence of the maxima is then approximately represented by a straight line and not by a logarithmic curve. This is equivalent to a continual increase in the logarithmic decrement as the oscillations decrease. Hence if we assign such a value of the logarithmic decrement as to fit the slope of the straight line at each point, this value increases with time as the amplitude dies away. This arises from the fact that the resistance of the spark increases as the amplitude of the oscillations decays.

Each successive oscillation is a little smaller than it would be if they diminished strictly according to a logarithmic law. Accordingly we can no longer predetermine the logarithmic decrement by calculation, but must arrive at it by experiment.

Experimentalists have, however, generally assumed that the decrement is constant, and that the decay of oscillations follows an exponential law.

The important matter is to determine the mean value of the decrement. Generally speaking, the greater part of the whole resistance of such oscillatory circuits as are used in wireless telegraphy is located in the spark gap, and a somewhat erroneous assumption is made if the resistance of the spark is taken as constant throughout the duration of a train of oscillations.

If, however, as a first approximation, we agree to take the spark resistance as constant, then several methods present themselves by

[3] See J. Zenneck, *Ann. der Physik*, March, 1904, vol. 13, p. 822; or *Science Abstracts*, July, 1904, vol. 7, A.

means of which we may determine experimentally the logarithmic decrement for non-radiative circuits containing a spark gap.

1st. We may find the ratio between two successive maximum currents or oscillations in opposite directions. This will give us the value of ϵ^{δ}, from which δ can be determined.

2nd. We may find the ratio between the square of the first maximum potential difference or current and the mean of the squares of all the potential differences or currents during a train. This, as shown below, will give us the value of $8n\delta$.

3rd. We may find the resistance of the spark independently of the rest of the circuit, and then if L is the high frequency inductance, and R′ is the high frequency resistance of the metallic part of the circuit, and r the resistance of the spark, we may determine the value of δ corresponding to r from the equation—

$$\delta = \frac{R' + r}{4nL} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

where n is the corresponding frequency of the oscillations.

The first-named method of determining the logarithmic decrement was suggested by Professor E. Rutherford in an important paper.[4] The process of measurement is as follows: Consider two similar coils of wire, A and B, placed in series in a discharge circuit. Let these coils be wound in opposite directions. Let two similar steel needles magnetized to saturation be placed in the coils A and B, their north poles facing in the same direction. If then a train of electric oscillations is created in these coils by discharging a condenser through them, it will be found that the reduction of magnetic moment of the needles is not the same in both cases. Let I_1, I_3, I_5, etc., be the maximum oscillations of the discharge in the one direction, and I_2, I_4, I_6, etc., be the maximum oscillations in the opposite direction. Then suppose that the half-oscillation I_1 is in such a direction as to increase the magnetization of the needle in the solenoid A, the needle in the coil A, being already saturated, will have no magnetic effect produced upon it by this first oscillation. The second oscillation, I_2, in the opposite direction, however, demagnetizes the surface skin, and the third oscillation, I_3, tends to remove the effect of the second, and so forth.

In the solenoid B, the first half-oscillation, I_1, is in such a direction that it demagnetizes the needle, and the second, I_2, tends to re-magnetize it in its original direction, and so on.

Since the maximum value of the first oscillation, I_1, is greater than that of the second oscillation, I_2, and the third greater than the fourth, and so on, the needle in the coil B will be more demagnetized than that in A. If, however, we increase the number of turns per centimetre on the coil A, until the magnetic effects on the two needles are exactly the same, then assuming that the values of the currents decrease in geometrical progression, the maximum value of the magnetic force due to the oscillation I_2 acting on the needle in the coil is equal to the maximum value due to the oscillation I_1 on the needle in coil B.

[4] See Prof. E. Rutherford, "On a Magnetic Detector of Electric Waves and some of its Applications," *Phil. Trans. Roy. Soc. Lond.*, A., 1897, vol. 189, p. 1.

Since the sum of a geometrical progression is proportional to its first term and to a function of its common ratio, it follows that the sum of $I_1 - I_2 + I_3 - I_4 +$ etc. is to the sum of $I_2 - I_3 + I_4 - I_5 +$ etc. in the ratio of I_1 to I_2, and hence the resultant effect of the entire train of oscillations in demagnetizing the steel needles is in each case proportional to the magnitude of the first effective demagnetizing oscillation. The statements above made follow, therefore, as a consequence of this fact.

Let N_1 and N_2 be the number of turns per centimetre of length which must be put on the two coils A and B respectively to make their demagnetizing effects equal.

$$\text{Then} \quad 4\pi N_1 I_1 = 4\pi N_2 I_2$$

$$\text{Therefore} \quad \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

Hence we have by definition—

$$\delta = \log_\epsilon \frac{I_1}{I_2} = \log_\epsilon \frac{N_2}{N_1}$$

and the logarithmic decrement is determined from the logarithm of

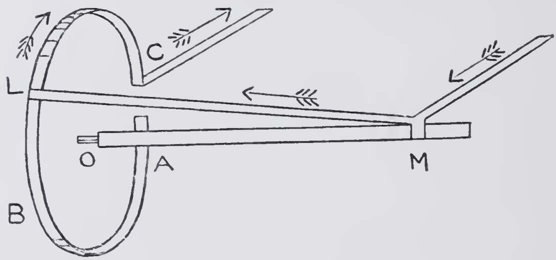


Fig. 1.—Rutherford's Method of measuring the Decrement of Electric Oscillations.

the ratio of the turns per centimetre of length of the two coils. The *damping* $\epsilon^{-\delta}$ is then equal to the ratio $\frac{N_1}{N_2}$.

Instead of employing two separate solenoids or coils, a more convenient plan was adopted by Professor Rutherford. A narrow piece of sheet zinc, ABC (see Fig. 1), was bent into an almost complete circle, 7 cms. in diameter. This was fixed upon a block of ebonite. At the centre of the circle a thin glass tube, OM, was placed, which serves as the axis of a metal arm, LM, which pressed against the circumference of a circle and could be moved round it. The magnet consisted of about 30 very fine steel wires 0·003 inch in diameter, made into a compound magnet 1 cm. long. The wires were insulated from each other by shellac varnish, and the small needle was fixed inside a thin glass tube which could be easily slipped in and out of the central glass tube, OM. Round the circumference of the zinc circuit was placed a divided scale, and the whole arrangement was placed in position before a small mirror magnetometer. The

magnetized needle was then magnetized to saturation and placed in position in the centre of the circular strip, and its action on the magnetometer was compensated by another magnet. An oscillatory discharge in the right direction was then passed round the circular circuit and a deflection of the magnetometer was observed, due to the partial demagnetization of the detector needle. The detector needle was then removed and magnetized again to saturation.

Since the magnetic field H at the centre of a circle due to an arc of length l is given by the expression—

$$H = \frac{lI}{a^2}$$

where a is the radius of the circle and I the current in it, we see that the magnetic force acting on the magnetic needle is proportional to the length of the arc traversed by the discharge.

A series of observations showed that the deflection of the magnetometer was approximately proportional to the magnetic force acting on the needle, provided the magnetic force was well below the value required to completely demagnetize the steel. To determine the damping of the oscillations, a discharge was passed in such a direction as to partly demagnetize the needle and the deflection of the magnetometer noted. The magnetic detector was then removed, magnetized to saturation and replaced, and a discharge passed in the opposite direction, and by various trial experiments the length of the effective arc of the circular circuit through which the discharge passed was adjusted in each case until the deflection was the same. When this was the case the ratio of the lengths of these arcs was proportional to the maximum values of the first and second oscillations. The damping $\epsilon^{-\delta}$ is then equal to the ratio of the lengths of the arcs of the circular circuit employed in the two experiments.

In this way the rate of decay of oscillations in many circuits was examined when the circuit contained a very short spark gap and the discharge circuit consisted of copper wires. It was found that the damping in this case was hardly appreciable. If, on the other hand, the copper wires were replaced by iron wires, then the damping rose to a large value and it also increased as the length of the spark gap increased, although not in the same proportion. The reason for this increase in the damping when iron wire is used is the absorption of energy due to the magnetic hysteresis. The oscillatory current is practically confined to the surface of the conductor, but it does penetrate sufficiently into the iron to effect a certain degree of magnetization, and involves, therefore, some amount of hysteretic energy loss. If the iron wire is electroplated with copper or is galvanized, then it is found that, as regards damping, the wire becomes practically identical with a solid copper or solid zinc wire. The following table of observations by Professor Rutherford (*loc. cit.*) gives the results of experiments made with spark gaps of various lengths in a copper-wire circuit, and shows the corresponding damping $\epsilon^{-\delta}$ and the total resistance R of the spark gap and circuit calculated from the formula—

$$R = 4nL\delta$$

Experiments on the Damping of Electric Oscillations.

Discharge circuit rectangular and made of copper wire, 184 cms. by 90 cms.; inductance of circuit, L = 7400 cms.; capacity, C = 2000 electrostatic units; frequency = 1·25 million per second.

Length of spark gap in millimetres.	The damping, or ratio of two first oscillations. $\epsilon^{-\delta} = \frac{I_2}{I_1}$	Total resistance of spark gap and circuit in ohms.	Resistance of spark in ohms.
0·6	0·98	—	—
1·2	0·97	1·1	0·7
2·4	0·93	2·6	2·2
3·7	0·90	3·7	3·3
4·9	0·79	8·4	8·0
6·1	0·70	12·4	12·0

In these experiments the calculated high frequency resistance of the wires of the discharge circuit was 0·4 ohm, so that the excess over above this value is the resistance of the spark.

Professor Rutherford found, as others have done, that the damping of the oscillations increased very rapidly with the length of the spark. It was also found that the damping depended on the capacity of the condenser used when the inductance and spark length were kept constant. For instance, with a spark gap having a length of 3·2 mms., and with different capacities, as in the table below, he found that the damping decreased with the increase of the capacity. It may be noted that to reduce capacity measured in electrostatic units to the equivalent in microfarads it is requisite to divide by 9×10^5.

Capacity in electrostatic units.	Damping.	Spark resistance in ohms.
1000	0·94	2·2
2000	0·90	2·6
4000	0·81	3·8

Similar experiments have also been made by the above-named method by Miss H. Brooks.[5] In this case the circuit in which the oscillations were set up consisted of a copper wire rectangle, the wire having a diameter of 0·7 mm. and the sides of the rectangle lengths of 145 and 125 cms. respectively. Hence the high frequency inductance was about 10^4 cms. The condenser used in the first experiments was a Leyden jar having a capacity of 0·00277 mfd. In other experiments another jar of less capacity was employed. The frequency of the oscillations was therefore close to 10^6. The quantity $4n\text{L}$ had a value 4×10^{10} C.G.S. units nearly, or 40 ohms, and the logarithmic decrement δ, assumed constant, was therefore

[5] See Miss H. Brooks, on "The Damping of Oscillations in the Discharge of a Leyden Jar," *Phil. Mag.*, vol. 2, ser. 6, p. 92.

equal to one-fortieth part of the total resistance of the spark and circuit reckoned in ohms, since $\delta = \dfrac{R' + r}{4nL}$.

The values of $\epsilon^{-\delta}$ and resulting values of δ for various spark lengths, found, as above described, by Professor Rutherford's method, are given in the table below.

Capacity of Condenser = 0·00277 *mfd.*

Spark length. S.	Damping. $\epsilon^{-\delta}$.	Logarithmic decrement. δ.
1 mm.	0·905	0·100
3 ,,	0·880	0·128
5 ,,	0·885	0·122
7 ,,	0·865	0·145
9 ,,	0·860	0·152
11 ,,	0·845	0·168
13 ,,	0·845	0·168

Capacity of Condenser = 0·000805 *mfd.*

Spark length. S.	Damping. $\epsilon^{-\delta}$.	Logarithmic decrement. δ.
2 mm.	0·875	0·133
3 ,,	0·840	0·175
5 ,,	0·765	0·269
7 ,,	0·680	0·387
9 ,,	0·590	0·529
11 ,,	0·515	0·663

The above numerical values of the damping $\epsilon^{-\delta}$ plot out into straight lines when the corresponding values of the spark length S are taken as abscissæ.

The earliest definite measurements of the logarithmic decrement of electric oscillations by the second method above mentioned were made by V. Bjerknes. It depends upon a comparison between the maximum value of the potential difference of the spark balls in an oscillating circuit and the root-mean-square value of the potential as measured by an idiostatic electrometer.[6] If an electrometer of the Kelvin type is constructed, having a suspended paddle-shaped "needle" and a pair of quadrants placed on opposite sides and against opposite ends of the "needle," we have an instrument which is sensitive to high frequency alternating potentials, and measures their root-mean-square value. If, then, the two quadrants are connected to the ends of a circuit in which oscillations are taking place, the quadrants are alternatively positively and negatively charged; but as the induced charges on the needle change places with the change of charge on

[6] See V. Bjerknes, "Ueber die Dämpfung schneller Electrischer Schwingungen," *Wied. Annalen der Physik*, 1891, vol. 44, p. 74.

the quadrants, the needle deflects constantly in the same direction. This deflection, if small, is proportional to the square root of the mean of the squares of the potential difference of the quadrants.

Since the train of oscillations always lasts far less than one second, we may say that this root-mean-square value of the potential difference is proportional to the square root of the integral $\int_0^\infty v^2 dt$, where v is the instantaneous potential difference.

We have seen (Chap. I., § 5) that when a condenser is discharged across a spark gap through a low resistance, the potential difference v of the plates at any time, t, can be expressed by an equation of the form—

$$v = V_0 \epsilon^{-at} \cos pt \quad . \quad . \quad . \quad . \quad . \quad (20)$$

where V_0 is the initial potential difference of the plates.

From the above equation we have—

$$\int_0^\infty v^2 dt = V_0^2 \int_0^\infty \epsilon^{-2at} \cos^2 pt = \frac{V_0^2}{4a} = U^2 \quad . \quad . \quad (21)$$

Hence U is the root-mean-square value of the potential difference of the condenser plates. But $a = 2n\delta$, therefore—

$$\delta = \frac{1}{8n} \cdot \frac{V_0^2}{U^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

and δ becomes known from the values of V_0, U, and n.

Since we cannot obtain a steady deflection of the electrometer by one single spark or train of oscillations, it is necessary to permit a series of discharges at a uniform rate of N per second to take place, and the value of δ is then given by the expression—

$$\delta = \frac{N}{8n} \cdot \frac{V_0^2}{U^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

The value of V_0 can be obtained from the spark length by the aid of the tables of spark potentials already given (see Chap. II., § 14), for the value of the potential difference of the plates of the condenser when the discharge begins is equal to the spark potential. The value of U is obtained by connecting the calibrated electrometer across the terminals of the condenser. The number of sparks per second, and also the frequency of the oscillations, must be obtained, the latter being calculated from the inductance and capacity in the circuit. In this manner we arrive at the value of the logarithmic decrement of the oscillations.

Some of Bjerknes' observations were made with an open oscillatory circuit of the Hertzian type, and for such an oscillator he found that the decrement per half-period depended on the length of the spark gap, but had values varying from 0·13 to 0·20, as the spark length increased from 1 to 5 mms. The damping in this case does not arise simply from resistance, but is mainly due to the radiation of energy in the form of electric waves, and this matter is further considered in § 8 of this chapter, and also in Chap. V. Whilst for an *open* or radiative circuit of the Hertzian type the decrement per half-period may amount to 0·2 or over, for a nearly closed circuit,

such as a Hertzian resonator, Bjerknes found that the decrement might be as low as 0·001.

5. Determination of the Mean Logarithmic Decrement in Oscillatory Circuits. Drude's Researches.—A very extensive research was conducted by Professor P. Drude on the influence of spark length and other factors on the logarithmic decrement of condenser circuits containing a spark gap. These results have a very practical bearing upon wireless telegraphy.[7]

The method he adopted was one which in principle originated with V. Bjerknes. If a primary oscillatory circuit containing a spark gap and condenser has oscillations set up in it, and if this circuit acts upon a closed secondary circuit containing a condenser but no spark gap, we have induced oscillations set up in this latter circuit. If the secondary circuit has such a form that its inductance can either be calculated or measured, and if the capacity in it is also known, as already shown, we can calculate its natural time period and deduce its high frequency resistance, and therefore logarithmic decrement, provided that the condenser in this secondary circuit is of such form that no energy is dissipated by radiation or in any other way except by resistance. If we insert in this circuit a thin wire at some point, we can, by means of a thermo-element or other means, determine the *integral* or *mean-square value* of the secondary current during a unit of time.

If this secondary circuit has such a form that we can vary its inductance, and therefore natural time period, we can find the corresponding values of the integral or mean-square value of the secondary current. For some particular inductance of the circuit this integral value of the secondary current will have a maximum value.

When this takes place the secondary circuit is said to be *in resonance* with the primary circuit (see § 9 of this chapter). V. Bjerknes and P. Drude[8] have shown that we can then determine the sum of the logarithmic decrements of the primary and secondary circuits from the observed values of the maximum integral current, and of any other value of the integral current not differing greatly from this critical one, when we know also the percentage deviation of the time period of the secondary circuit in the last case from that which sets up resonance.

Let i_2 denote the secondary current at any instant, and J^2 the integral current, so that—

$$J^2 = \int_0^\infty i_2^2\, dt$$

Also let T_2 denote the periodic time of the secondary circuit. Then let J_m^2 and T_m denote the values of these quantities when the secondary circuit is so adjusted as regards inductance that J^2 has its maximum value. Again, let—

$$T_2 = T_m(1 + \eta) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

[7] See P. Drude, "Die Dämpfung von Kondensatorkreisen mit Funkenstrecke," *Ann. der Physik*, 1904, vol. 15, part 4, p. 709.

[8] See V. Bjerknes, *Ann. der Physik*, 1895, vol. 55, p. 121, "Ueber Elektrische Resonanz." See P. Drude, *Ann. der Physik*, 1904, vol. 13, p. 512, "Ueber induktive Erregung zweier Elektrischer Schwingungskreise mit anwendung auf Perioden und Dämpfungsmesung, Tesla transformatoren, und drahtlose Telegraphie."

Since $T_2 = \frac{1}{n_2}$ and $T_m = \frac{1}{n_1}$, where n_1 and n_2 are the frequencies of the two circuits, we have—

$$\eta = \frac{n_1 - n_2}{n^2} = \frac{n_1}{n_2} - 1$$

Let δ_1 and δ_2 denote the logarithmic decrements of the primary and secondary circuits as we have defined them.

Drude, following Bjerknes, then shows that the sum of the decrements of the two circuits is given by the equation—

$$\delta_1 + \delta_2 = \pi\eta\sqrt{\frac{J^2}{J_m^2 - J^2}}\,[9] \quad . \quad . \quad . \quad . \quad . \quad (25)$$

Near resonance when n_2 is nearly equal to n_1 the quantity η becomes identical with $1 - \frac{n_2}{n_1}$.

We have translated Drude's formula into our notation, but in referring to the original paper the reader should note that his logarithmic decrement is double of ours, being defined as due to a complete instead of a semi-period, and also that he takes J, and not J^2, to represent the integral current. We shall indicate in a later section of this chapter (see § 14) the method by which the above formula is obtained.

Drude's experiments were conducted with a secondary circuit which had the form of a rectangle, the sides being made partly of metal rods and partly of tubes, so that by sliding them in and out of each other the length of the rectangle, and therefore its inductance, could be varied and calculated. A condenser of known capacity was inserted in this circuit, and also a short piece of fine wire, to which a thermo-junction was attached. This last was connected to a galvanometer. Drude first proved that when a single spark discharge was made in the primary circuit the induced secondary oscillation heated the fine wire, and therefore the thermo-junction, and produced a "throw" or ballistic deflection of the galvanometer coil proportional to the integral effect of the secondary current or oscillation.

He then showed that if l_m was the length of side of the secondary rectangle corresponding to resonance or to J_m, and if dl was any small variation of this length, the quantity η was equal to $\frac{1}{2}\frac{dl}{2l_m}$, and hence the above formula (25) transforms into—

$$\delta_1 + \delta = \frac{\pi}{2}\cdot\frac{dl}{l_m}\sqrt{\frac{J^2}{J_m^2 - J^2}} \quad . \quad . \quad . \quad . \quad (26)$$

His experimental procedure was then to take a number of observations of the integral current J^2 corresponding to various values of the side of the secondary rectangle, and to plot a curve called a *resonance curve*, in which ordinates represented the "throw" of the galvanometer and abscissæ, the length of the side of the rectangle forming the

[9] See P. Drude, *Ann. der Physik*, 1904, vol. 15, p. 716, to which we must refer the reader for the rather long proof of the above formula, which is derived from another equation (84) in an article by P. Drude in *Ann. der Physik*, vol. 13, p. 527. A proof of this formula is given in § 14 of this chapter (see equation 145).

secondary circuit. For the fuller explanation of the nature of a resonance curve, the reader must refer to § 14 of this chapter.

Drude then calculated for any given length of side the inductance, and hence the decrement δ_2, of the secondary circuit.

The observations were then reduced as follows: Corresponding to each particular length of side of the secondary circuit there is a certain "throw," s, of the galvanometer when a single primary spark is taken which measures the secondary integral current. If s_1 and s_2 represent two throws corresponding to two lengths of side, l_1 and l_2, one greater and one less than the value s_m corresponding to resonance by equal amounts, we can say that—

$$dl = \frac{l_1 - l_2}{2} \text{ and } l_m = \frac{l_1 + l_2}{2}$$

$$\text{and} \quad J^2 = \frac{s_1 + s_2}{2} \text{ and } J_m{}^2 = s_m$$

Therefore we have—

$$\delta_1 + \delta_2 = \frac{\pi}{2} \cdot \frac{l_1 - l_2}{l_1 + l_2} \sqrt{\frac{(s_1 + s_2) \div 2}{s_m - (s_1 + s_2)/2}} . \quad . \quad . \quad (27)$$

Taking a number of values of l and s from the resonance curve Drude deduced the values $\delta_2 = 0{\cdot}0083$, $\delta_1 = 0{\cdot}08$.

The above values are the semi-period decrements. They show therefore, that the primary circuit is much more damped than the secondary circuit.

By a large number of observations made with various spark lengths and with spark balls of various materials, Drude arrived at the following conclusions:—

1. For every condenser circuit with a spark gap there is a certain length of spark for which there is a minimum damping.

2. For zinc spark balls and small sparks this critical spark length lies between 1 and 2 mms., and the logarithmic decrement between 0·05 and 0·08.

3. To obtain small damping, it is necessary to employ a condenser absolutely free from brush discharges or dielectric hysteresis, and this can only be done by constructing the condenser of metal plates placed in petroleum oil.

4. Zinc spark balls give the smallest damping, and preserve their active effect in producing an oscillatory spark longest. Cleaning the surfaces increases the spark activity and reduces the decrement.

5. The integral effect in the secondary circuit increases at first with increasing spark length and then diminishes again.

6. The resistance of the spark depends very much upon the capacity and inductance in the oscillating circuit. Hence we cannot speak of a spark of given length having a definite resistance. With a large capacity and small inductance the spark resistance for given length is less than with small capacity and large inductance.

7. The effects of increased air pressure, and of light falling on the spark balls, and of the material of the spark balls on the logarithmic decrement, were carefully investigated. Drude says that spark balls made of zinc are superior to those made of brass in their active spark-producing qualities.

8. The effect of brush discharges on the edges of condenser plates, and of dielectric hysteresis when glass was employed as a dielectric, showed itself in increased total logarithmic decrement, and therefore in a decreased number of oscillations per train.

From the point of view of practical wireless telegraphy by electric waves, the important deduction to be made from these experiments is the advantage of employing short sparks. In those cases in which high charging potentials are required, it is better to gain this by using a number of short sparks in series rather than one long one. This can be done by placing a number of insulated metal plates in series with very small spaces between them, and connecting the two terminal balls to the oscillating circuit (see Chap. VIII., § 16).

6. The Resistance of an Oscillatory Spark.—Since the resistance of the spark in a condenser circuit traversed by electric oscillations is an important factor in determining the decay of the oscillations, considerable attention has been given to experimental methods for determining directly the resistance of an oscillatory electric spark and its variation with quantity, frequency, and spark length.

The factors which can be varied are—

(i.) The length of the spark.

(ii.) The quantity of electricity which passes initially, as measured by the spark potential and the capacity of the condenser discharging.

(iii.) The oscillation frequency determined by capacity and inductance of the circuit.

(iv.) The group frequency, or number of oscillatory sparks per second.

(v.) The material and form of the discharging surfaces.

(vi.) The pressure and nature of the gas in which the spark takes place.

A full examination of the effect of all these factors has not yet been made. In many cases the conditions of experiment have not been stated accurately, and between most of the experiments on spark resistance so far conducted a considerable difference of conditions has existed, so that comparisons are difficult. Some observers have endeavoured to measure the equivalent ohmic resistance of a single oscillatory spark. Since, however, in wireless telegraphy and Hertzian wave work generally we nearly always employ a continuous series of oscillatory sparks, the investigations made with isolated sparks are not of predominant interest.

A knowledge of the logarithmic decrement as obtained from the ratio of the first two oscillations gives us a lower limit to the resistance of the spark, provided we know the high frequency resistance of the rest of the circuit. Thus, in the experiments on damping made by Miss Brooks by Rutherford's method, already described, the inductance of the metallic part of the discharge circuit was 10^4 cms. The capacity employed was 0·00277 mfd., and hence the frequency was nearly 10^6. The quantity $4n\mathrm{L}$ was therefore nearly 4×10^{10} cms. per second, or 40 ohms. The high frequency resistance of the wire of the discharge circuit was found to be 0·6 ohm as calculated by Lord Rayleigh's formula. Hence if r is the spark resistance in ohms and δ the logarithmic decrement, and if we

assume the spark resistance constant during the train of oscillations, we have—

$$\delta = \frac{0{\cdot}6 + r}{40}$$

Taking the values of δ given in the first table on p. 173 for spark lengths of 1, 3, 5, 11 mms. respectively, we calculate the corresponding spark resistance as follows:—

Spark length. S.	Logarithmic decrement. δ.	Spark resistance r.
1 mm.	0·100	3·4 ohms
3 ,,	0·128	4·52 ,,
5 ,,	0·122	4·28 ,,
11 ,,	0·168	6·12 ,,

It must be noted that these observations refer to the resistance of single sparks or discharges, and not to the resistance produced when a large number of discharges per second are made across the spark gap. There is evidence that in this last case the resistance of the train of sparks is very much less, for the same spark length, than the values given in the above table. Accordingly, these results are valid only for the circumstances of the experiment.

Miss Brooks found that the pressure of the air round the spark exercised a very marked effect on the damping, reduction of pressure within certain limits reducing the damping.

An interesting deduction is made in her paper from known facts as to the electric charge carried on gaseous ions, viz. that the expenditure of energy in the manufacture of the ions just necessary to carry the discharge across the gap does not account for the whole of the damping, but it is evident that a vastly larger number of ions are created by the discharge than is necessary to carry the discharge across. It is to the recombinations of these ions that the heat and light of the spark are probably due.

Experiments were also made on the effect of variation of the capacity of the condenser. It was found that when this capacity was greater than about 0·001 mfd. the damping was practically independent of the capacity, but that for very small capacities the damping increased rapidly with decrease of capacity. Hence the damping reaches a steady state when the discharge current exceeds a certain very moderate value.

Professor A. Slaby has also made extensive investigations on the resistance of an oscillating spark.[10] His method consisted in forming an oscillating circuit containing in series the ordinary spark gap S_1 of fixed length, a spark gap, S_2, of variable length, a condenser, C, and inductance, L, and a variable resistance, R, in the form of a graphite rod, as well as a sensitive hot-wire ammeter, A (see Fig. 2). The spark gap of variable length was

[10] See *Elektrotechnische Zeitschrift*, Oct. 27, 1904; also *The Electrician*, Nov. 11, 1904, vol. 54, p. 150.

shunted by an electrolyte resistance, U, consisting of a tube containing a solution of sulphate of copper having a resistance of 410 ohms. This permitted the condenser to be charged, but did not sensibly shunt the disruptive discharge. The variable spark gap was then altered in length from zero, and, corresponding to various lengths, readings of the ammeter were taken. This gave the current (R.M.S. value) in terms of the spark length. The spark gap S_2 was then made zero, the graphite resistance R varied, and readings of the ammeter again taken. This gave the current in terms of the graphite resistance. These two sets of observations were plotted as curves with current as ordinates, and for equal ordinates they showed the resistance of the spark gap expressed in ohms. In repeating these experiments, the author has found it to be an advantage to employ a long inductance coil of low resistance instead of the tube of sulphate of copper, and in place of the graphite rod to use a long column of 10 per cent. dilute sulphuric acid of variable length.

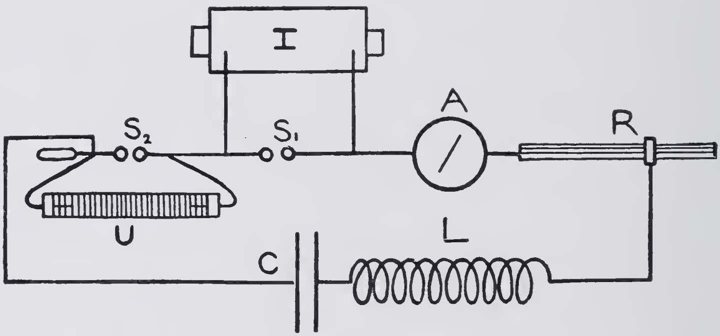


FIG. 2.—Slaby's Method of measuring the Resistance of Oscillatory Electric Sparks.

The final results indicated that the resistance of the spark gap rises parabolically with spark length for small lengths, but afterwards increases linearly. Professor Slaby found that with increase in the capacity of the oscillating circuit the resistance of the spark per millimetre of length decreased.

The following results, taken from the figures given in Professor Slaby's paper, show the resistance of the spark for various spark lengths when the capacity in the circuit had a value of 360 electrostatic units, or 0·0004 mfd.

Spark length.	Spark resistance.
1 mm.	0·25 ohms.
2 ,,	0·90 ,,
3 ,,	2·30 ,,
4 ,,	5·0 ,,

The spark resistance for given lengths depends greatly upon the capacity used, that is, upon the quantity of electricity discharged across the gaps. This is shown by the curves in Fig. 3, taken from Professor Slaby's observations. There is also good evidence that the

spark resistance varies with the number of discharges per second when these are numerous. Again, if the conductance of the spark is plotted in terms of the frequency, it is found that as the period increases the conductance diminishes, at first linearly and afterwards more rapidly.

For all periods, with the same spark voltage, small spark lengths have more conductivity per unit of length than long ones. Hence the advantage of using a number of small spark gaps in series, instead of one long one, in certain cases where small damping is required, is very great.

Professor Slaby found that, in the case of an ordinary wireless telegraph aerial wire, the damping due to the resistance of the wire itself is negligible. For a 120-foot copper wire antenna 3 mm. in diameter it amounts at most to about 0·8 per cent. Hence we may say that in the case of the oscillating circuits used in Hertzian wave

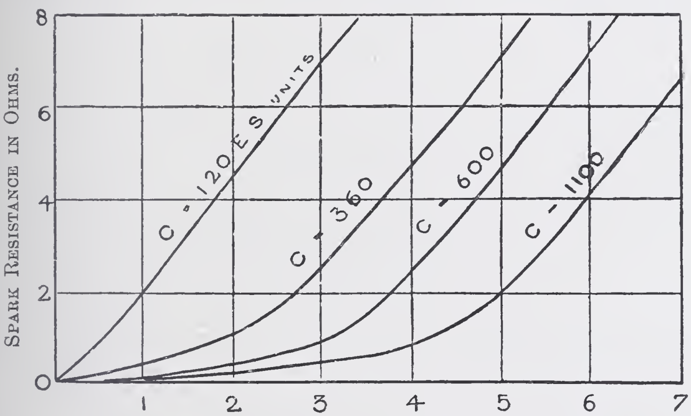


Fig. 3.—Curves showing Spark Resistances for Various Spark Lengths and Capacities (Slaby). The numbers on the curves denote the capacity corresponding to them reckoned in electrostatic units.

telegraphy the damping of the oscillations is almost entirely due to the resistance of the spark and to the radiation of energy from the aerial wire.

To obtain, therefore, a wave train not rapidly damped, the resistance of the spark and of the rest of the circuit must be very small, or the supply of energy must be very large if radiation is taking place.

Another method of measuring the spark resistance in the case of a non-radiative circuit has been employed by several observers. It depends on the fact that if a condenser is discharging with oscillations through nearly closed circuit partly metallic but containing a spark gap, and if the condenser itself does not in any way dissipate energy internally by hysteresis or brush discharges, then the rate at which the energy is given out by the condenser must be equal to the sum of the rates at which it is being dissipated in the metallic part of the circuit and in the spark.

If we call J the root-mean-square value of the instantaneous discharge current i when reckoned in amperes, so that

$$J^2 = N\int_0^\infty i^2 dt$$

where N is the number of discharges per second, and if R′ is the high frequency resistance of the circuit; then J^2R' is the rate at which energy is dissipated in the metallic part of the circuit. Again, if r is the resistance of the spark, J^2r is the rate at which energy is dissipated in the spark. We have then to find experimentally the value of the root-mean-square discharge current for the discharges per second.

This may be done as follows :—

We employ a hot-wire ammeter suitable for measuring currents of 1 to 10 amperes or upwards, the hot wire of which consists of a number of fine copper wires placed in parallel. If we refer to the formula for the high frequency resistance of round copper given in Chap. II., viz.—

$$R' = R\left\{\pi d\sqrt{\frac{n}{\rho}} + \tfrac{1}{4}\right\}$$

we shall see that if $n = 10^6$ we have—

$$\frac{R'}{R} = 40d \text{ nearly} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

Hence, for this frequency, when d is as small as 0·25 mm. there is no sensible increase in resistance. Accordingly, a copper wire of No. 40 S.W.G. size has not an appreciably greater resistance for currents of a frequency of 10^6 than for steady currents. If, therefore, we make an ammeter as in Fig. 32, Chap. II., and calibrate it with continuous currents, we shall be able to read off on it the root-mean-square value of a high frequency current passing through it. Suppose, then, that we place such an ammeter in a circuit consisting of a round-sectioned copper wire bent in the form of a rectangle, and complete this circuit by a condenser and spark gap. The condenser must be of such a type that there is no internal dissipation of energy in it, and is best made of metal plates placed in highly insulating oil. We then take a series of discharges at the rate of N per second, the sparks passing at regular intervals. It will be found that the ammeter gives a steady deflection and indicates a current, say, of A amperes. If we calculate from the inductance, capacity and ohmic resistance of the circuit, the high frequency resistance R′, the quantity A^2R' gives us the rate at which energy is being dissipated in the metallic part of the circuit.

If we know the spark potential V corresponding to the spark length, then the quantity $\frac{1}{2}NCV^2$ gives us the rate at which energy is derived from the condenser. Hence the quantity $\frac{1}{2}NCV^2 - A^2R'$ must be the rate at which energy is being expended in the spark, and therefore the resistance of the spark r must be given by the expression—

$$r = \frac{\frac{1}{2}NCV^2 - A^2R'}{A^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

In the above expression, however, we assume that the resistance of the spark is that of the spark which is due to the condenser

discharge alone. The actual spark which happens is, however, an admixture of two sparks, or rather of a spark and an arc. At the moment when the dielectric between the spark balls breaks down, not only does the condenser begin to discharge with oscillations, and thus form the true oscillatory spark, but the induction coil or transformer or other source of charging voltage produces a discharge across the gap which is of the nature of an electric arc. The greater this arc the less will be the resistance between the discharge balls. Hence it is not quite easy to define what is meant by spark resistance, and the discrepancy between the results of various observations on spark resistances may to some extent be due to the fact that arc and spark resistance are mixed up together in different proportions. We can determine to what extent there is a true electric arc effect mixed up with the true spark discharge as follows: If C is the capacity of the condenser in microfarads, and V the potential in volts corresponding to the spark length, and N the number of charges per second, then the charging current in amperes flowing into the condenser should be $\frac{NCV}{10^6}$, since this is the quantity per second delivered to the condenser. If we then insert a hot-wire ammeter in between the spark balls and the induction coil or transformer, and find a greater value than that given by the above expression for the current flowing out of the source of supply, we know that the difference between the observed and calculated current must be passing across the spark gap as an electric arc.

The chief difficulty, however, in applying this last-mentioned method of determining spark resistance is in the correct measurement of the spark frequency and spark voltage. The spark frequency can be found by means of the author's spark counter (see Chap. II., § 15). It is by no means correct to assume that there is only one discharge spark for each break of the circuit of the induction coil or alternation of the transformer, whichever is used to create the discharges. If the spark gap is short there may be several oscillatory discharges per break of the induction coil or per alternation of the transformer. On the other hand, if the spark gap is long and the capacity large there may be a lesser number of oscillatory sparks than alternations of the charging potential. The second difficulty consists in correctly estimating the spark voltage, that is, the potential to which the condenser is charged. When the spark balls become hot the spark voltage for a given spark length is decreased, and the only way to determine the voltage is to place in parallel with the actual spark balls used another pair consisting of brass balls of a known diameter, say, 2 cms., and ascertain to what distance these last balls must be approached in order that discharge may just begin to take place between them, and from that distance to determine the corresponding spark voltage by the tables given in Chap. II., § 14. Even when the spark frequency and spark voltage are correctly estimated, it is found that great discrepancies exist between the spark resistances obtained for sparks of known lengths. This is unquestionably due to the different degrees in which true electric arc discharge is mixed up with spark discharge.

Professor Slaby has also investigated the effect of change of size

and material of the spark balls upon the spark resistance. He found that for short sparks (less than 4 mms. in length) an increase in diameter of the spark balls was accompanied by an increase of spark resistance, but that for longer sparks the difference was imperceptible. As regards the effect of material, he tried balls of 1 cm. in diameter made of brass, copper, lead, aluminium, magnesium, cadmium, zinc, tin, iron, steel, silver, gold, and platinum, and spark lengths from 0·5 to 3 mms., using apparently a very small capacity. His results showed that for the 0·5-mm. spark cadmium and tin and silver balls gave spark resistance about half that of the other metals, which were about equal, but for the 3-mm. sparks iron and steel balls gave spark resistance about 30 per cent. greater than that of the remaining metals.

The following table gives the chief results :—

Spark length in millimetres.	Spark resistance in ohms between 10 mms. diameter balls made of—									
	Brass.	Pb.	Cu.	Al.	Mg.	Cd.	Zn.	Sn.	Fe.	Ag.
0·5	0·9	0·9	1·3	1·3	1·3	0·5	1·0	0·5	0·9	0·6
1·0	2·4	1·8	2·8	2·8	2·8	1·5	2·2	1·2	2·2	1·5
1·5	4·0	3·3	4·4	4·6	5·5	3·0	3·5	2·5	4·5	2·5
2·0	5·9	5·5	6·4	7·1	9·5	5·2	5·6	4·6	7·7	3·8
2·5	8·9	9·3	9·3	10·6	14·6	8·4	8·4	8·2	11·8	5·8
3·0	12·8	14·6	12·6	15·5	—	12·4	12·2	13·3	16·4	8·9

The results show that a far less spark resistance for a 3-mm. spark voltage could be obtained by using four tin balls placed 1 mm. apart, so as to obtain three 1-mm. sparks in series between tin surfaces, than by using a single spark of 3 mms. in length between brass and iron balls.

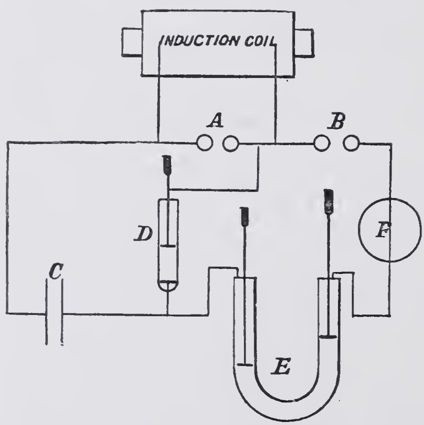


Fig. 4.—Arrangement of Apparatus used in Measurement of Spark Resistances at University College, London. *E*, **U**-tube of dilute sulphuric acid; *D*, high resistance of copper sulphate solution; *F*, hot-wire ammeter; *B*, adjustable spark balls; *C*, condenser.

The author has repeated these experiments of Professor Slaby, but has found it convenient to substitute for the graphite resistance R in Fig. 2 a **U**-tube, E, full of dilute sulphuric acid of known strength and resistivity (see Fig. 4). A thermometer immersed in this liquid gives its temperature, and a greater or less length of the column of fluid can be inserted in the oscillatory circuit by moving up or down metallic piston electrodes in the arms of the **U**-tube. In place of

the tube D of sulphate of copper an inductance spiral may be used. Using this apparatus and spark balls (B) of iron, zinc, or brass 1·25 inch in diameter, the author determined the spark resistance for various lengths of spark and for a capacity of 1070 mmfds. as shown in the curves in Fig. 5. These curves show that with increasing spark length the resistance of the spark between iron balls increases rapidly when compared with that between brass or zinc balls.

It should be noticed that the method adopted by Professor Slaby and by the author of measuring spark resistance involves a constant current in the discharge circuit, and may therefore be said to give the spark resistance for various spark lengths corresponding to a certain constant current. In radiotelegraphy, by the spark method, we generally find that the length of the spark itself determines the quantity of electricity which passes at each discharge, and hence the

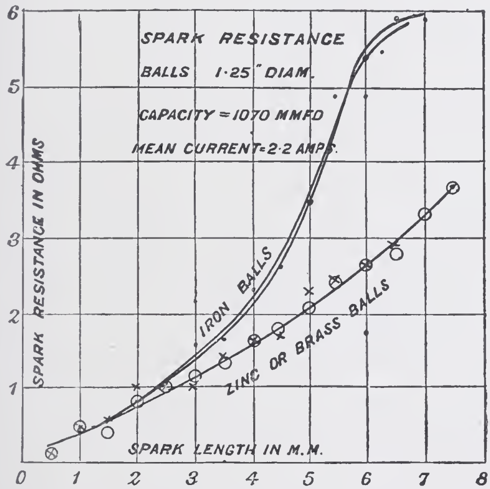


FIG. 5.—Spark Resistances for Various Spark Lengths between Iron, Brass, and Zinc Balls. (Fleming.)

resonance method of measuring spark resistance has been preferably employed, for then the oscillatory current is not constrained to have any constant value, but is allowed to take the value determined by the capacity and inductance of the oscillatory circuit. This method consists in determining first a resonance curve for the oscillatory circuit in the manner described in the last section of this chapter. If, then, we employ for the metallic part of the oscillatory circuit which contains the spark gap, such a circuit that we can calculate its high frequency resistance R′, and if we call the resistance of the spark r, then if L is the inductance and n the frequency and δ_1 the decrement of the spark circuit, we have seen that $\delta = \dfrac{R' + r}{4nL}$, and hence we can calculate r when we know the other quantities.

Measurements of oscillatory spark resistance have also been made by the above method by G. Rempp (see *Ann. der Physik*, 1905, vol.

17, p. 627, or *Science Abstracts*, 1905, vol. 8, A., p. 606). Rempp employed the Bjerknes resonance method above described, the secondary circuit being very loosely coupled with the primary circuit containing the spark gap. He employed rather small capacities, 270 to 6860 mmfds., and long spark gaps, 0 to 5 cms. He considered he had proved that as the spark length increases from zero the spark resistance falls to a minimum, which occurs at about 3 mm. for small capacities and 6 mm. for large capacities, and that after this is reached the spark resistance increases with spark length very rapidly for small capacities, but much more slowly for larger capacities. He found, as others have done, that beyond a certain capacity the spark resistance ceases to diminish with increase of capacity. Some of his results are delineated in Figs. 6 and 7.

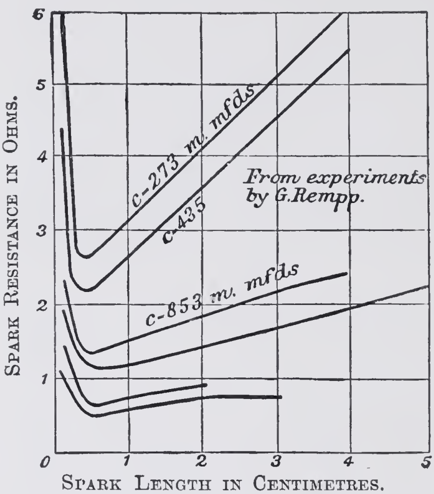


Fig. 6.—Curves showing Results of Rempp's Observations on Spark Resistance for Various Spark Lengths and Capacities. The rise in the curves with increasing spark length is a spurious effect due to "fringing" or glow discharge at edges of coatings of the Leyden jars used.

These results of Rempp have been shown by W. Eickhoff (see *Phys. Zeitschrift*, 8 Jahrgang, No. 15, p. 494, 1907) to be vitiated by the fact that the brush discharge at the edges of the coatings of the Leyden jars used as capacity, is a source of dissipation of energy, which is equivalent to an increase in spark resistance. The magnitude of the decrement of the trains of oscillations is increased by every source of energy dissipation, such as heat produced in the circuits, or in the condenser dielectric. Hence the glow discharge over the edges of the condenser coatings is, unless allowed for, reckoned as energy loss due to the spark resistance, and hence would make the calculated spark resistance appear too large.

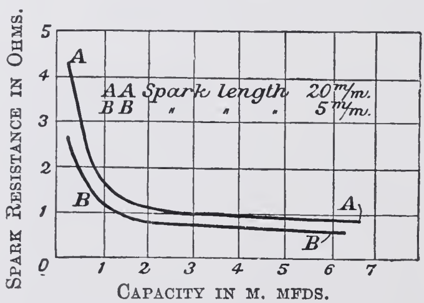


Fig. 7.—Rempp's Observations on Spark Resistance for Various Capacities and Spark Lengths.

The author repeated some of Rempp's experiments, using a condenser consisting of metal plates immersed in oil, and under these conditions glow discharge is absent. When this was done resistance

measurements were made of sparks of various lengths, and no evidence was found of such a rise in spark resistance for long sparks as is indicated in Rempp's curves in Fig. 6.

The author carried out, in conjunction with Mr. Richardson, a series of experiments on the decrement and spark resistance of oscillatory circuits, both when the spark was subjected to an air blast and when it was not blown upon. The circuit consisted of a rectangle of copper wire 0·162 cm. in diameter, the sides of the rectangle being respectively 34·17 cms. and 142·1 cms. The inductance was 5012 cms. and the high frequency resistance 0·31 ohm. for currents of a frequency of $1·25 \times 10^6$. The capacity in series with this rectangle was an oil condenser having a capacity of 0·002645 mfd. The spark balls were brass balls 3 cms. in diameter. The spark resistance was measured by the Bjerknes resonance method for various spark lengths with and without an air blast on the spark balls. The decrements per semi-period and the spark resistances are given in the following table. The frequency employed was in all cases near to $1·25 \times 10^6$.

SPARK RESISTANCES AND LOGARITHMIC DECREMENTS FOR SHORT HIGH FREQUENCY SPARKS.

Spark length in mm.	Air blast on spark gap.		No air blast on spark gap.	
	Log. dec. per half period of circuit.	Spark resistance in ohms.	Log. dec. per half period of circuit.	Spark resistance in ohms.
1	0·0467	0·86	0·0423	0·75
2	0·0443	0·80	0·0447	0·81
3	0·0397	0·68	0·0383	0·65

Experiment shows that the spark resistance tends to fall slightly with increasing current in the oscillation circuit, and that the air blast conduces to render this current more uniform.

7. Magnetic Damping.—If we employ as the oscillatory circuit a wire made of magnetic material, then, in addition to the damping or decay of the oscillations caused by the resistance of the wire and that due to the spark (if any) in the circuit, there is an additional damping due to the work absorbed in producing the magnetic changes in the circuit. Bjerknes found for equal-sized resonators made of wire 0·5 mm. thick a logarithmic decrement of 0·017 if the metal was copper, but 0·13 if it was iron or nickel.[11] The fact that such magnetic damping occurs is proof that magnetic metals retain their magnetizable qualities, and therefore hysteretic energy dissipating power, even when the magnetizing force is being reversed millions of times per second.

Bjerknes showed by experiment that an iron or nickel wire,

[11] See V. Bjerknes, *Wied. Ann. der Physik*, 1892, vol. 47, p. 69, and vol. 48, p. 592, 1893. The above numbers are half of those given by Bjerknes to adjust them to our definition of the log. dec.

when used as an oscillatory circuit, has sensibly greater damping than a copper one, also that the deposition of the thinnest film of electro-deposited copper on the iron wire sufficed to annul this extra damping. This also was confirmed by similar experiments made by Professor Rutherford and by Miss Brooks.[12] This fact alone affords proof that electric oscillations are confined to the surface skin of the wire.

We have already seen (see Chap. II., p. 122) that this concentration of the current at the surface is more marked with magnetic conductors than in the case of non-magnetic materials.

At one time it was considered doubtful whether exceedingly rapid alternations of magnetic force could magnetize iron, and therefore give up energy to it in consequence of magnetic hysteresis.[13] There

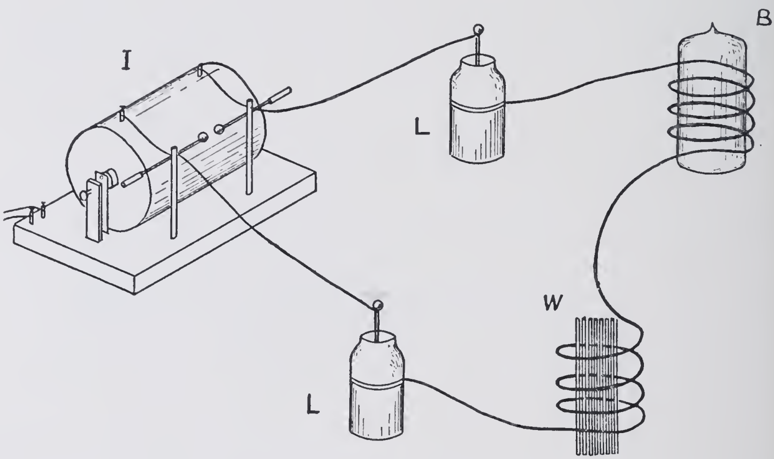


Fig. 8.—I, Induction Coil; L, L, Leyden Jars; B, Vacuum Bulb; W, Iron Core introduced into Coil.

are many facts, however, which show that the penetration of the high frequency current into the iron conductor, though small, is sufficient to bring about surface magnetization, and therefore hysteretic loss. Suppose we set up a pair of condensers or Leyden jars and connect their outer coatings by a thick copper wire, in which a couple of loops of two or three turns are formed, and their inner coatings to the secondary terminals of an induction coil (see Fig. 8).

If in one of the loops formed in this circuit we introduce a glass bulb, B (see Fig. 8), containing air or any other gas highly rarefied, we find that at each discharge of the coil a bright ring of light is formed in the bulb. This is an induced discharge in the rarefied gas acting as a secondary circuit. The discharge may be so adjusted that the introduction of any object into the other loop in the

[12] See also Miss H. Brooks, *Phil. Mag.*, ser. 6, vol. 2, p. 92.
[13] See Hertz, *Ann. der Physik und Chemie*, 1888, vol. 34, p. 558.

condenser circuit which absorbs the energy of the oscillation quenches the glow in the gas.

Professor Sir J. J. Thomson has shown that it is possible to arrange the experiment so that the introduction of a cylinder of copper, or bundle of copper wire, into the second coil of the primary circuit does not much affect the luminous discharge in the gas, but the introduction of a similar-sized cylinder of iron or equal bundle of iron wires, W (see Fig. 8), immediately destroys it. This, Professor Thomson points out, must be a consequence of the energy absorption involved in magnetizing the iron, so that although its electrical conductivity is much less than copper, yet, owing to the fact that its permeability is much higher than unity, its damping effect on the electrical oscillations is on the whole greater.[14]

Accordingly, we are led to the conclusion that even at these high frequencies the iron is magnetized by the action of electrical oscillations, and possesses a permeability which is probably as high as 300 or 400.

Direct photographic proof of the magnetizability of iron by oscillatory discharges has been obtained by Dr. E. W. Marchant, and the two photographs of oscillatory sparks shown in Figs. 19 and 20 of Chap. I., illustrate this fact well.[15] The first photograph is that of the spark taken when a condenser of 0·06 mfd. was discharged through a coil having an inductance of about 5 microhenrys, the potential of the discharge being 13,500 volts. The coil contained in this case no iron core. The second photograph shows the spark when a core of 550 fine iron wires, No. 28, was inserted into the paper tube on which the wire was wound.

These photographs show that the effect of the iron is to increase the time period or to slow down the oscillations, and in addition, owing to the increase in the permeability of the iron as the discharge current dies away, we see that the interval between successive oscillations increases—in other words, the oscillations are no longer isochronous.

Again, it has been shown by Professor J. J. Trowbridge that electric oscillations on iron wires are damped out more quickly than on copper wires, and that there is an energy absorption in the case of iron greater than can be accounted for by its electrical resistance.[16]

An excellent investigation by Mr. C. E. St. John has confirmed the above results.[17] By creating stationary electric waves on wires, Mr. St. John has shown that the inductance of iron wires is greater than that of similar-sized copper wires when made into circuits of the same form, and conveying electric oscillations of a frequency of about 56 millions by 3·4 to 4·3 per cent., and he has confirmed the result that in the case of iron wire there is a more rapid damping out of the oscillations.

[14] See "Researches in Electricity and Magnetism," p. 323; also see J. J. Thomson, *Phil. Mag.*, Nov. 2, 1891, p. 460.

[15] Taken from a letter by Dr. Marchant to *Nature*, Aug. 30, 1900.

[16] See Prof. J. Trowbridge, "The Damping of Electric Oscillations on Iron Wires," *Phil. Mag.*, Dec., 1891, ser. 5, vol. 32, p. 504.

[17] See Mr. C. E. St. John, "Wave Lengths of Electricity on Iron Wires," *Phil. Mag.*, Nov., 1894, ser. 5, vol. 38, p. 425.

The experiments show that the permeability of the iron, even at this frequency, on an average is still as high as 385.

In discussing the various forms of detectors for electric waves, we shall have to notice some which depend for their action upon the fact that electric oscillations can annul the magnetic hysteresis of iron, as well as give up their energy to it in consequence of hysteresis.

The practical deduction to be made from the above facts is that the rate at which electric oscillations decay on an iron wire is much greater than that at which they would decay if a non-magnetic wire of the same size is used; in other words, the logarithmic decrement is greater. This is in some small degree due to a difference in electric resistance, but chiefly to the magnetic permeability of the iron. Hence the moral is, that iron wires must not be used for constructing oscillatory circuits in which it is desired that the oscillations shall be as little damped as possible. Hence iron must not be used for wireless telegraph aerials. Nevertheless, well-galvanized iron wire can be used, since it has been shown that a very thin layer of zinc placed on iron is sufficient to confine the electric oscillations to the zinc, and prevent them from penetrating to the iron beneath and giving up their energy to it.

8. **Damping due to Radiation and other Causes**.—It will have been evident, from the facts considered in the two previous sections, that any source of dissipation of energy in the oscillatory circuit shows itself by causing damping or decay in the oscillations. Hence not only does ohmic resistance of the circuit or spark gap and magnetic hysteresis (if any) in the wire circuit create damping, but dielectric hysteresis (if any), or true dielectric conduction, or brush discharges over the dielectric surface of the condenser used, are also possible additional causes. Also, if energy is being sent off from the oscillatory circuit in the form of electric waves or radiation, this also creates very considerable damping. In a later chapter we shall study more particularly the forms of circuit which can thus radiate. Meanwhile we may say that if the distance between the two surfaces which form the condenser is small compared with the linear dimensions of the smaller of the two plates, then the circuit containing this condenser is called *a closed oscillation circuit*. If, however, the distance is large compared with the linear dimension of the smaller of the two surfaces, the circuit is called *an open oscillation circuit.*

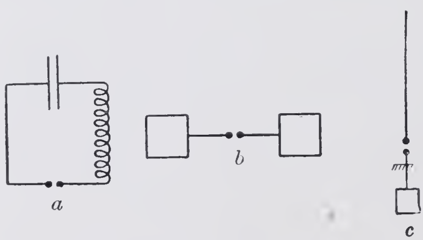


FIG. 9.—*a*, Closed Oscillation Circuit; *b*, *c*, Open Oscillation Circuits.

Typical instances of closed or feebly radiative and open or strongly radiative circuits are shown in Fig. 9.

Again, if we couple a nearly closed oscillatory circuit consisting of a condenser, C, spark gap, S, and inductance coil, L, with another open circuit, M (see Fig. 10), the open circuit can have electric oscillations created in it inductively by the other, and these oscillations can in turn create a disturbance called

an electro-magnetic wave in the surrounding æther. Hence energy is, so to speak, sucked out of the closed circuit by the radiating circuit, and considerable damping ensues. The closed circuit alone cannot radiate if the condenser plates are close together, but it can radiate if coupled with an open one.

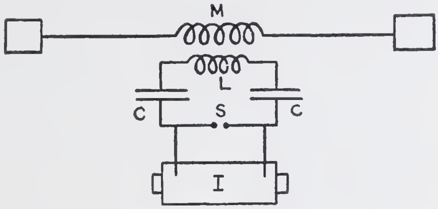


FIG. 10.—Inductive Coupling of a Closed and Open Oscillation Circuit.

If oscillations are created in a nearly closed circuit by connecting the spark balls to the secondary terminals of an induction coil, then experiment shows that these oscillations are very persistent, the logarithmic decrement is small, and the damping almost wholly due to the resistance of the spark. Several dozen oscillations may take place before the electrical disturbance dies away. On the other hand, if we set up oscillations in an open circuit, the decay of the oscillations is much more rapid, and is almost entirely due to the fact that they impart their energy to the surrounding æther, and create electric waves by a process discussed more in detail in a subsequent chapter. There are, therefore, very few oscillations, a dozen at most, before the electrical motion has practically ceased. There is, therefore, a very great difference between these two forms of circuit. The closed circuit is called a persistent oscillator, and the open one a good radiator.

As we can always avoid using iron or magnetic wires for oscillatory circuits and also condensers in which internal dielectric energy losses occur, we need not concern ourselves further with the increase in damping which arises from hysteresis losses, whether magnetic or dielectric. On the other hand, we are unable to arrest the decay of oscillations due to resistance or radiation. The total logarithmic decrement in any oscillatory circuit is therefore made up of two parts—

(i.) That due to resistance (in German called *Joule'sches decrement*), and (ii.) that due to radiation (*Strahlungs decrement*).

The relative numerical value of these two decrements, or parts of the total decrement, depends upon the nature of the oscillatory circuit.

In the case of an open circuit oscillator, such as a Hertzian oscillator, consisting of two rods placed in line with their ends nearly touching, and furnished with spark balls, or in the case of a Marconi aerial, consisting of a pair of spark balls, one connected to the earth and the other to a vertical insulated wire, the radiation decrement very greatly exceeds the resistance decrement.

In the case of a certain circular Hertz resonator, consisting of a nearly closed metallic circuit interrupted by an air condenser, S. Lagergren found that the radiation decrement was only 0·071, whilst the resistance decrement was 0·0064, the total decrement being 0·077.[18]

[18] See S. Lagergren, "Ueber die Dämpfung Electrischer Resonatoren," *Wied. Ann. der Physik*, 1890, vol. 64, p. 290.

M. Planck, however, found that the radiation decrement for an open or radiative circuit of the Hertzian type was as high as 0·15, whilst the resistance decrement was only 0·045, the total decrement being 0·195.[19]

Bjerknes has shown that for certain equal oscillators made respectively of copper and platinum, in the case of the copper 75 per cent. of the energy lost is due to radiation, and 25 per cent. is dissipated by resistance; whereas for the platinum 37·5 per cent. was lost by radiation and 62·5 per cent. by resistance.

The predetermination of the radiation logarithmic decrement can only be achieved in a few cases by reason of the difficulty of the calculations.

Taking the case of a linear oscillator consisting of two metal spheres at the extremities of two metal rods, provided at their inner ends with small spark balls (see Fig. 11), Hertz calculated the energy stored up and the energy lost per oscillation to be as follows[20]:—

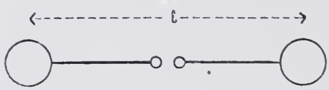


FIG. 11.—Dumb-bell Oscillator. (Hertz.)

Let l be the length of the oscillator, measured from ball to ball, let λ be the wave length of the radiation emitted, and Q the charge on either half of the oscillator just before the spark discharge begins. Then Hertz shows that the energy lost by radiation from this oscillator per half period is given by the expression—

$$\frac{8\pi^4 Q^2 l^2}{3\lambda^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

For the proof of the above formula we must refer the reader to § 9, Chap. V., of this treatise.[21] Also in § 10, Chap. V., it is shown as a consequence that if C is the capacity of one part of the oscillator with respect to the other, and δ is the radiation logarithmic decrement as defined for the semi-period—

$$\delta = \frac{16\pi^4 l^2 C}{6\lambda^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

We may apply this to a case given by Hertz himself (see "Electric Waves," p. 150).

The oscillator consisted of two metal rods, each 5 mms. in diameter and 50 cms. in length. To the ends of these rods were attached metal spheres, 30 cms. in diameter (see Fig. 11). The rods were placed in line, with a spark gap of 7·5 mms. between the small knobs terminating the metal rods.

We have first to calculate the capacity of one half of the oscillator with respect to the other. The capacity of a sphere in electrostatic units is numerically equal to its radius in centimetres.

[19] See Max Planck, *Wied. Ann.*, 1897, vol. 60, p. 599. These figures are, of course, the decrements per half period. Planck gives the decremental values per whole period.

[20] See Hertz, "Electric Waves," English translation by D. E. Jones, p. 150.

[21] See also "Æther and Matter," Adams prize essay, by Sir Joseph Larmor, Sec. R. S., p. 225, where the same formula is deduced by a different method.

The capacity of one sphere with respect to the other is, however, only half of the above value, because the two spheres may be considered to be in series with each other. Hence the capacity with which we are concerned is equal to 7·5 cms. Inserting this value for C in the expression (31), and the values $\pi^4 = 97{\cdot}4$, $l = 100$, and $\lambda = 480$ (as given by Hertz), we find for the value of the radiation decrement δ—

$$\delta = \frac{16 \times 97{\cdot}4 \times (100)^2 \times 7{\cdot}5}{6 \times (480)^3} = 0{\cdot}17 \quad . \quad . \quad . \quad (32)$$

To obtain the total decrement, we have to add to this the resistance decrement. Since the resistance is almost entirely due to the oscillatory spark, that of the rod being negligible, it will be sufficient to calculate it by the formula $\frac{r}{4n\mathrm{L}}$, where r is the resistance of the spark, n the frequency, and L the inductance of the rods.

The high frequency inductance of the straight rod, 100 cms. in length ($= l$) and 5 mms. in diameter ($= d$), can be approximately calculated by the formula—

$$\mathrm{L} = 2l\left(\log_\epsilon \frac{4l}{d} - 1\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Hence L = 1134 cms. The frequency is therefore nearly 50×10^6.

The value of $4n\mathrm{L}$ is therefore 204×10^9, or nearly 200 ohms.

We have already seen that the resistance of a 7-mm. oscillatory spark may be rather over 5 ohms, and hence the logarithmic decrement due to resistance would then be about $\frac{5}{200}$, or 0·025. Hence, for the oscillator in question, when in operation we have a radiation decrement equal to 0·17, and a resistance decrement equal to 0·025, and a total logarithmic decrement of 0·2 nearly. Hence the loss of energy by radiation per oscillation is more than 10 times as great as that due to the resistance of the spark.

V. Bjerknes, in an important paper,[22] has shown, by the method already explained, that the total damping of a Hertzian oscillator is very large, and he obtained experimentally for a certain Hertzian oscillator total logarithmic decrements with various spark lengths, as follows :—

Spark length.	Total logarithmic decrement per half period.
1 mm.	0·14
2 ,,	0·15
3 ,,	0·16
4 ,,	0·17
5 ,,	0·20

The gradual increase in the value of δ is without doubt due to the steady increase in the spark resistance with spark length, which increases the part of the decrement due to resistance. The agreement between the calculated value of the total decrement and that obtained experimentally by Bjerknes for a 5-mm. spark is very close.

In another case, Bjerknes measured the logarithmic decrement

[22] See V. Bjerknes, "Über die Dämpfung Schneller Electrischer Schwingungen," *Wied. Ann. der Physik*, 1891, vol. 44, p. 74.

of a Hertz radiator consisting of two metal rods, each 5 mms. in diameter and 50 cms. in length, having attached at the ends circular discs of metal 30 cms. in diameter. The opposite ends terminated in spark balls, and the rods were placed in line with each other.

The capacity in free space of a circular disc of diameter D cms. in electrostatic units is $\frac{D}{\pi}$. Hence in this case the capacity of each disc in space was nearly 10 cms. The capacity of one half of the oscillator with respect to the other is therefore 5 cms., or a little more, on account of the capacity of the rod.

Bjerknes found that the wave length of the wave radiated from the oscillator was 431·2 cms. Hence, substituting in the formula for δ the values $C = 5$, $\lambda = 431{\cdot}2$, $l = 100$, we have—

$$\delta = \frac{16 \times 97{\cdot}4 \times (100)^2 \times 5}{6 \times (431{\cdot}2)^3} = 0{\cdot}16$$

The resistance decrement, for the Hertz oscillator previously mentioned, has a value of about 0·025. Hence the total decrement should be 0·185.

Bjerknes found experimentally, for this oscillator, a total logarithmic decrement (per half period) of 0·2, which agrees fairly well with the above calculated value.[23]

An important case, which, however, can only be treated approximately, is that of the Marconi aerial wire in its original form. As we shall see in a subsequent chapter, Marconi made telegraphy without wires by means of electric waves possible by his invention of the earthed antenna or linear radiator.

A vertical insulated wire has a spark ball at the lower end which is placed in apposition to another spark ball connected to the earth. The two balls are connected to the secondary terminals of an induction coil. When the coil is in action the aerial wire is charged and discharged alternately with oscillations across the spark gap. It is well known that these oscillations are strongly damped. We can obtain a fair approximation to the logarithmic decrement and to the damping, as follows:—

The capacity of such an aerial wire with respect to the earth is not very different from that of a very prolate ellipsoid of revolution whose major axis is equal to the height h of the aerial wire, and its minor axis to the diameter d of the wire.

An expression for the capacity of such a prolate ellipsoid in electrostatic units has already been given, obtained from the general expression for the capacity of an ellipsoid (see Chap. II., p. 179), and it is[24]—

$$C = \frac{h}{2 \log_\epsilon \frac{2h}{d}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

Provided that the lower end of the wire is not too near the earth,

[23] See V. Bjerknes, *Bihang till K. Svenska Vet. Akad. Handlungen*, 1893, 20 Afd., I. nr. 5, II. p. 6, "Ueber Electrische Resonanz;" see also M. Planck, *Wied. Ann. der Physik*, 1897, vol. 60, p. 595.

[24] J. A. Fleming and W. C. Clinton, "On the Measurement of Small Capacities and Inductances," *Phil. Mag.*, ser. 6, vol. 5, p. 492; see also Chap. II., § 7.

the above expression enables us to calculate within about 5 or 10 per cent. the capacity of a single vertical Marconi aerial wire.

It can be shown that if an ellipsoid of revolution is divided by equidistant parallel planes taken perpendicularly to its axis of revolution, each of the zones into which the surface is divided has the same electrical capacity *in situ*. Hence if the vertical wire is not too near the earth we may assume that its capacity per unit of length is the same all the way up it. As a matter of fact, in actual aerial wires the bottom portions have larger capacity per unit of length than the upper ones, by reason of their greater proximity to the earth.

We have in the next place to calculate the *electric moment* of such a linear oscillator.

In discussing the case of the Hertzian oscillator above, we have assumed that the electrical capacity was limited to the capacity of the two spheres placed at the outer ends of the linear oscillator or wire interrupted in the centre by a spark gap.

In the case of the single-wire antenna, we have capacity distributed all along it, and we must calculate what must be the capacity which, concentrated at the top of the aerial, would, when charged with the potential found at the summit, give a total electric charge equal to that actually resident on the wire. We shall show in the next chapter (see Chap. IV., § 7) that when the fundamental oscillations are excited on such a wire the maximum potential increases all the way up the wire from the earthed end to the top in accordance with a simple sine law. This fact has been experimentally confirmed. Hence if V denotes the maximum potential of an element of the wire at any distance, x, from the earth, and if V_h is the potential at the top of the aerial wire of height h, then the expression—

$$V = V_h \sin\left(\frac{\pi}{2} \cdot \frac{x}{h}\right)$$

gives us a value for V which complies with the terminal conditions. Let c be the capacity of the wire per unit of length, and hence the whole capacity of the wire C is given by—

$$C = ch = \frac{h}{2 \log_\epsilon \frac{2h}{d}}$$

The maximum charge of electricity dQ on any element of length dx of the wire is then—

$$dQ = cVdx = \frac{V_h \sin\left(\frac{\pi}{2} \cdot \frac{x}{h}\right)dx}{2 \log_\epsilon \frac{2h}{d}}$$

To obtain the whole charge of the wire, we have to integrate the above expression between the limits h and 0. Hence we have—

$$Q = \frac{V_h}{2 \log_\epsilon \frac{2h}{d}} \int_0^h \sin\left(\frac{\pi}{2} \cdot \frac{x}{h}\right)dx = \frac{V_h}{2 \log_\epsilon \frac{2h}{d}} \cdot \frac{2}{\pi} h = \frac{2}{\pi} CV_h$$

The quantity $\frac{2h}{\pi}\mathrm{CV}_h$ is called the *electric moment* of the antenna.

Hence if we suppose the capacity of the wire itself to be zero, but a capacity equal to $\frac{2}{\pi}$ of that of the real wire to be placed at the summit and charged to a potential V_h, that charge will be equal to the actual charge distributed on the wire. Hence in the general expression (31) for the radiation decrement of an oscillator we have to substitute for the symbol C, which denotes the capacity of one part of the oscillator with respect to the other, the expression—

$$\frac{2h}{2\pi \log_\epsilon \frac{2h}{d}}$$

since this last expression is the equivalent terminal capacity of the single-wire antenna earthed at the lower end.

Also we have to substitute for the symbol l the height h of the wire. Again, we shall show in Chap. IV. that the wave length λ of the radiated wave is *approximately* four times the height of the aerial, so that $\lambda^3 = 64h^3$. Making these substitutions, we find that for the vertical earthed oscillator or Marconi aerial wire the radiation decrement δ is given by—

$$\delta = \frac{\pi^3}{24 \log_\epsilon \frac{2h}{d}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

since $\pi^3 = 31{\cdot}006$, the above formula is very nearly equivalent to—

$$\delta = \frac{1{\cdot}25}{\log_\epsilon \frac{2h}{d}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35a)$$

This expression gives us radiation decrement per half-period, and agrees very well with experimental results. A formula for the damping of a linear oscillator has been given by M. Abraham (see *Wied. Ann.*, 1898, vol. 66, p. 435) nearly identical with (35) (see Chap. V., § 11).

Suppose we consider the case of a vertical wire of diameter 0·1 inch and height 180 feet, such as is used in Marconi wireless telegraphy. For this wire $\frac{2h}{d} = 43{,}200$, and $\log_\epsilon \frac{2h}{d} = 10{\cdot}66$. Hence—

$$\delta = \frac{125}{1066} = 0{\cdot}117, \text{ or, say, } 0{\cdot}12$$

Since the inductance L of such an aerial wire will be about 10^5 cms., and the spark resistance r may be perhaps 5 ohms, whilst the frequency n will be of the order of 10^6, we see that the resistance decrement $\frac{r}{4n\mathrm{L}}$ will be about 0·0125, and hence, as in the case of the Hertzian oscillator, the radiation decrement is about 10 times the resistance decrement. The total decrement will be 0·133, or, say, 0·14 per half-period.

To sum up, we may say that for any ordinary form of Hertzian oscillator, including a Marconi vertical wire aerial radiator, the logarithmic decrement per half-period due to radiation has a value not far from 0·1 or 0·2, whilst the logarithmic decrement per half-period due to the resistance of the spark is very considerably less, say, about 0·01 or 0·02.

This means that the oscillations are practically extinguished in about ten complete oscillations or less. For since $\epsilon^{20 \times 0 \cdot 2} = \epsilon^4 = 54 \cdot 6$, a logarithmic decrement of 0·2 implies that the tenth *complete* oscillation has a value which is only 2 per cent. of the first oscillation, and is therefore practically negligible. To facilitate the calculation of the decay of oscillations for given decrements, we append a table of the powers of ϵ for various fractional and integer exponents. In Fig. 12 are shown a series of curves which are the plotting of the equation $y = \epsilon^{-\delta}$ for different values of δ marked on the curves.

VALUES OF ϵ^{δ}.

$\epsilon = 2 \cdot 71828$.

δ	ϵ^{δ}.	δ	ϵ^{δ}.	δ	ϵ^{δ}.	δ	ϵ^{δ}.
0·00	1·000	0·10	1·105	1·00	2·72	5·50	244·6
0·01	1·010	0·20	1·220	1·50	4·48	6·00	403·4
0·02	1·020	0·30	1·35	2·00	7·39	6·50	763·6
0·03	1·030	0·40	1·49	2·50	12·18	7·00	1096·0
0·04	1·041	0·50	1·63	3·00	20·10	7·50	1808·0
0·05	1·052	0·60	1·82	3·50	33·12	8·00	2981·0
0·06	1·062	0·70	2·02	4·00	54·6	8·50	—
0·07	1·072	0·80	2·22	4·50	88·0	9·00	—
0·08	1·083	0·90	2·46	5·00	148·4	10·00	—
0·09	1·094						

If the amplitude of the first oscillation is taken as unity, the ordinates of any curve show the successive amplitudes at the end of each period, corresponding to decrements per half-period marked on the curve.

An expression for the ratio between the radiation decrement δ_r and the resistance decrement δ_s has been established by Max Planck,[25] who arrives at the formula—

$$\frac{\delta_r}{\delta_s} = \frac{8\pi^2}{3}\left(\frac{l}{\lambda}\right)^2 \frac{3 \times 10^{10}}{r \times 10^9} \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

where r is the spark resistance in ohms, and l and λ are the length and wave length of the oscillator. Since λ is from 4 to 5 times l, and r may be 5 to 10 ohms generally, we have—

$$\frac{\delta_r}{\delta_s} = 26 \cdot 32 r \frac{l^2}{\lambda^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

[25] See Max Planck, "Über Electrische Schwingungen welche durch Resonanz erregt und durch Strahlung gedampft werden," *Wied. Ann. der Physik*, 1897, vol. 60, p. 577.

which may have a value from 5 to 16 or so, according as we take $r = 5$ or 10 and $\frac{\lambda^2}{l^2} = 16$ or 25.

A formula very similar to that given by Planck can be deduced for the ratio of the energy expended in radiation and that expended in the spark.

Consider the first half period $\left(\frac{T}{2}\right)$ of an oscillation in which the maximum current is I_1, and therefore the root-mean-square value $\frac{I_1}{\sqrt{2}}$. We have, for the value of the energy expressed in electrostatic

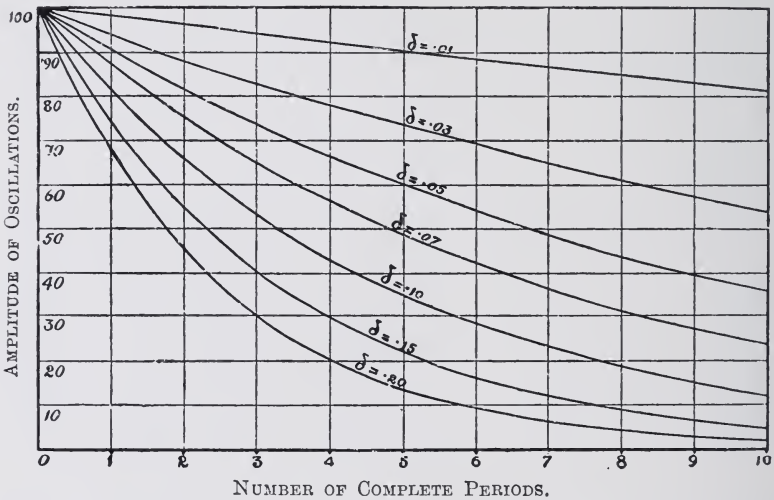


FIG. 12.—Curves showing the Amplitude of the Oscillatory Potential or Current at the end of each Complete Period for Various Values of the Decrement δ per semi-period.

units (E_s) expended in the spark (of which the resistance is r ohms) in the first half-period, the expression—

$$E_s = \frac{r \times 10^9 \times I_1^2 \times T}{9 \times 10^{20} \times 2 \times 2} \quad . \quad . \quad . \quad . \quad . \quad (38)$$

The numeric 9×10^{20} in the denominator is the factor for converting resistance measured in electromagnetic units to resistance measured in electrostatic units.

In one half-period the energy expended in radiation, also expressed in electrostatic units (E_r), is given by Hertz's formula—

$$E_r = \frac{8\pi^4 Q^2 l^2}{3\lambda^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

As we have already shown (see p. 216, equation (13)) that—

$$C^2p^2V^2 = Q^2p^2 = I_1^2\epsilon^\delta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

Substituting the above value of Q^2 in Hertz's expression, we have—

$$E_r = \frac{2\pi^2\epsilon^\delta l^2 I_1^2}{3n^2\lambda^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (41)$$

Hence, dividing equation (41) by (38), and remembering that for electric radiation through space $n\lambda = 3 \times 10^{10}$, we obtain—

$$\frac{E_r}{E_s} = \frac{8\pi^2}{3}\epsilon^\delta\left(\frac{l}{\lambda}\right)^2\frac{3 \times 10^{10}}{r \times 10^9} \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)$$

Hence the ratio is independent of the amplitude, and is the same for each half-oscillation, and therefore for the whole train.

The formula (42) differs from Planck's formula (36) only by the factor ϵ^δ, and this is nearly unity if δ is small. This factor, however, is not unity if δ has a value such as 0·2, for then ϵ^δ is then near to 1·2. It is easy to show that if the decrement δ has such a small value that ϵ^δ is unity, then we must have—

$$\frac{E_r}{E_s} = \frac{\delta_r}{\delta_s}$$

where δ_r is the radiation decrement and δ_s the resistance decrement. Taking the expression for δ_r derived from Hertz's formula for the radiation per half-period (see Chap. V., § 10), and expressing the capacity C in *farads*, we have—

$$\delta_r = \frac{16\pi^4 l^2 C u^2}{6\lambda^3 \,.\, 10^9}$$

where $u = 3 \times 10^{10}$.

Also, since the resistance decrement is given by—

$$\delta_s = \frac{r}{4nL}$$

where r is the spark resistance in ohms and L is the circuit inductance in henrys, we have, by division, remembering that $4\pi^2 CLn^2 = 1$—

$$\frac{\delta_r}{\delta_s} = \frac{8\pi^2 l^2 u}{3r\lambda^2 \,.\, 10^9}$$

But the above formula is Planck's (36), and differs only from (42) by the absence of the factor ϵ^δ. Hence generally—

$$\frac{E_r}{E_s} = \frac{\delta_r}{\delta_s}\epsilon^\delta = \frac{80\pi^2}{r}\epsilon^\delta\left(\frac{l}{\lambda}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

where δ is the total decrement.

We may apply this last formula (43) to calculate the *radiative efficiency* of a Marconi aerial radiator having the form of a simple wire of length l and a total decrement $\delta = 0·2$, which would be the case if the spark had a length, say, of 5 mms., and therefore a resistance of about 5 ohms. Under these conditions $\epsilon^\delta = 1·22$ nearly and $r = 5$. Then, since the wave lengths λ of the radiated wave would be

rather more than four times the length l of the radiator, we have approximately—

$$\frac{E_r}{E_s} = 12{\cdot}2$$

and we may say that the energy radiated is 12 times that dissipated in the spark, or the efficiency of radiation is nearly 90 per cent.

9. Free and Forced Oscillations. Resonance.—In all departments of physics in which we are concerned with vibrating bodies or systems of any kind, we find ourselves confronted with a phenomenon which is generally described by the term *resonance*. This term was originally coined in connection with certain effects noticed in acoustics, but its real origin being dynamical, it has been generalized and extended.

FIG. 13.—Rowland's Syntonic Pendulums.

In its simplest form it can be exemplified by an experiment due to Professor H. A. Rowland.[26] Let a wooden lath (see Fig. 13) be provided at the bottom with a weight, and let it be suspended at the top so as to be capable of vibrating like a pendulum in one plane. It is then said to have one degree of freedom. At a point just below the point of suspension let a steel pin be placed through the rod, so as to project out at right angles to the rod and the plane of oscillation. When the rod vibrates, this pin makes small excursions to and fro. Provide a number of strings with bullets at the bottom and a loop formed in the string at the other end, by which to hang these simple pendulums on the pin of the master pendulum. Let these strings be of such length that one of the pendulums is equal in length to the master, one is one-third the length, one is a quarter, and one is an odd length, no exact fraction. If then the master pendulum is set in vibration and any of the simple pendulums be successively hung on the pin, these last will be set in sympathetic vibration if its natural time period T, expressed by $T = 2\pi\sqrt{\frac{l}{g}}$ where l is the length of the string and g is the acceleration of gravity, is equal to that of the master pendulum to some exact submultiple of it. Otherwise the simple pendulum will not be set in motion by the other.

The time period for small swings of the master pendulum is given by the expression—

$$T = 2\pi\sqrt{\frac{I}{K}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

where I is the moment of inertia of the mass, and K is the quotient of the torque required to produce a small angular displacement, θ, by the angle θ. The proof of the above formula is simple. If we neglect all sources of energy dissipation such as friction, we may say that the restoring torque $K\theta$ is proportional to the product of the moment

[26] See H. A. Rowland, "Collected Physical Papers," p. 29.

of inertia round the axis of rotation and to the angular acceleration. Accordingly—

$$-I\frac{d^2\theta}{dt^2} = K\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

The left-hand quantity has the minus sign because the displacement is assumed to decrease with the time. Hence the equation of motion is—

$$I\frac{d^2\theta}{dt^2} + K\theta = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (46)$$

A particular solution of the above equation is—

$$\theta = A \sin \beta t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

Since $\sin \beta t = \sin (\beta t + 2\pi) = \sin \beta\left(t + \frac{2\pi}{\beta}\right)$, it follows that $\frac{2\pi}{\beta}$ is equal to the periodic time of the motion, because after the lapse of a time T the displacement repeats itself. Hence—

$$\frac{2\pi}{\beta} = T, \text{ or } \frac{2\pi}{T} = \beta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (48)$$

By differentiating (47) and substituting it in the original equation (46), we find that $\beta = \sqrt{\frac{K}{I}}$. Hence we have—

$$T = 2\pi\sqrt{\frac{I}{K}}$$

If, then, exceedingly small impulses act on the system, at intervals exactly equal to its free periodic time, each one of these impulses acts to increase the effect of the last, and very large oscillations may be accumulated by extremely small individual impulses.

This fact can be illustrated by a number of simple instances. Stretch a string somewhat loosely between two fixed supports, and attach to it two simple pendulums. Set one of these in vibration in a plane perpendicular to the vertical plane which contains the stretched string. It will communicate small impulses to the loose support and through it to the other pendulum, which will thereby be set in motion (see Fig. 14). Since, however, action and reaction are equal and opposite, the first pendulum is brought gradually to rest as it communicates its motion to the second. Then the second conveys back the energy to the first, and so the pendulums continue to set each other in motion and transfer the energy of motion from one to the other.

The general dynamical principle that any system capable of being set in vibration can have large oscillations created in it by infinitely small impulses coming at intervals equal to its own free period of vibration has extensive application.

It is not only applicable to cases of mechanical motion, but to electrical systems of conductors possessing capacity and inductance disturbed by electromotive force. If there be any case in which a system has potential energy when disturbed, and is subject to such constraints that its potential energy is increased by a displacement, it will, if left to itself, tend to go back to the condition of minimum potential energy, and in so doing will overshoot the mark. The acquired kinetic energy is then returned to the potential form, and a

vibrational condition is set up in which energy is continually transformed from potential to kinetic and *vice versâ* at each transformation, some of the kinetic being dissipated as heat.

We have already seen that an inductance, L, in series with a capacity, C, constitutes an electrical system having one degree of freedom. An electromotive force acting on it causes an increase in the potential energy, and if the system is then abandoned to itself it will execute electrical oscillations, the time period T of which is given by the formula—

$$T = 2\pi\sqrt{\mathrm{CL}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (49)$$

If, then, small electromotive forces act on the system at regular intervals they will increase continually this potential energy, provided that their time period agrees very exactly with that of the circuit. A very little difference, however, is sufficient to prevent the cumulative effect.

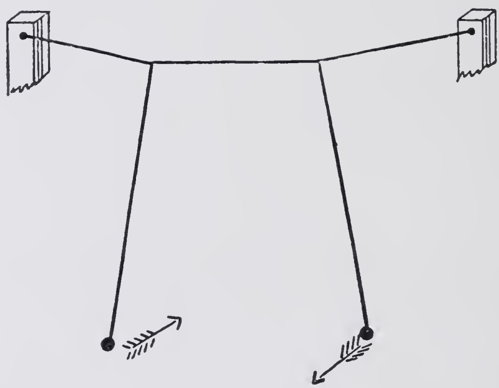


FIG. 14.—A Pair of Coupled Pendulums.

In dealing with this part of the subject we shall see that we meet continually with the product $\sqrt{\mathrm{CL}}$, viz. the product of the square root of the capacity of a condenser and the inductance of a coil placed in series with it. It is convenient to call this product the *oscillation constant* of the circuit.

Again, in considering the separate parts, we find the phenomena are determined by the quantities $\mathrm{L}p$ or $2\pi n\mathrm{L}$ and $\frac{1}{\mathrm{C}p}$ or $\frac{1}{2\pi n\mathrm{C}}$, where n is the frequency. The quantity $\mathrm{L}p$ is now called the *reactance* of the inductive circuit, and the author has employed the term *captance* to signify the quantity $\frac{1}{\mathrm{C}p}$.

The quantity $p = 2\pi n$, or the number of oscillations in 2π seconds, is conveniently called the *oscillation number*.

The reactance and captance are quantities of the dimensions of resistance, and may be measured in ohms. Hence, if there be a circuit consisting of a condenser and inductance in series, which is submitted to simple periodic or sinoidal electromotive force, the

current in the circuit creates two electromotive forces, one of which opposes and the other helps change of current. If I is the maximum value of the current, then LpI is the maximum value of the counter-electromotive force due to reactance or inductance, and $\frac{I}{Cp}$ is the maximum value of the adjuvant electromotive force due to captance or capacity. The *vector equation* connecting current I and impressed electromotive force E (maximum values being understood) is—

$$E = RI + j\left(LpI - \frac{I}{Cp}\right) \quad . \quad . \quad . \quad . \quad . \quad (50)$$

where j stands for the sign of perpendicularity, or that the vector $\left(LpI - \frac{I}{Cp}\right)$ is at right angles to that denoted by RI. Accordingly, the impressed electromotive force must have components which have a vector sum equal to that of the several electromotive forces acting against or with it. Hence, by the ordinary rules for obtaining the size of vectors expressed by complex quantities, we have [27]—

$$(I) = \frac{(E)}{\sqrt{R^2 + \left(Lp - \frac{1}{Cp}\right)^2}} \quad . \quad . \quad . \quad . \quad . \quad (51)$$

where (E) and (I) denote the mere numerical values of E and I. Accordingly, if we keep E, n, and R constant, and vary L and C, the current I will have a maximum value when $Lp = \frac{1}{Cp}$, or when the reactance is equal to the captance, or when—

$$LCp^2 = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (52)$$

The above is the condition for resonance in a single circuit.

If we attempt to test the above formula by placing a condenser of variable capacity across the terminals of an alternator, we are met with the difficulty that change in the capacity alters the phase difference of the current and electromotive force of the alternator, and therefore affects its excitation.[28]

In this case the result found is a mixed effect. Nevertheless, the measurement of the current shows that as the capacity or inductance are varied, the current tends to a maximum value, which it reaches when the condition is fulfilled. Under these conditions, the inductive circuit in series with a capacity acts as if it were perfectly non-inductive, and the current has the value it would have if a non-inductive resistance equal to the resistance of the inductive circuit was substituted for the capacity and inductance employed.

Hence, if we plot out the current flowing in the circuit under constant sinoidal electromotive force, or the electromotive force corresponding to constant current, when the capacity or inductance are varied we have a curve such as that shown in Fig. 15, which

[27] For a short explanation of the method of dealing with alternating current problems by means of these complex or vector expressions, the reader is referred to the next section of this chapter.

[28] See J. A. Fleming, "The Alternate Current Transformer," vol. ii. p. 394, where some of these mixed resonance effects in the case of alternators and transformers working on cables having capacity are discussed.

rises sharply to a maximum value, which it reaches when the inductance, capacity, and frequency are so related that $LCp^2 = 1$. When we are employing high frequency electromotive forces, very striking effects can be produced with quite small inductances and capacities placed in series with each other, and the circuits so formed are remarkably responsive to exceedingly small periodic electromotive forces which agree in period with the natural time period of the circuit so formed.

To obtain these cumulative or resonance effects, it is necessary, however, to employ circuits with small damping, or which are persistent oscillators. We can illustrate the chief facts, as follows:—

Let two circuits, P and S (see Fig. 16), be formed, each of 8 or 10 turns of insulated wire wound round square frames, the side of each

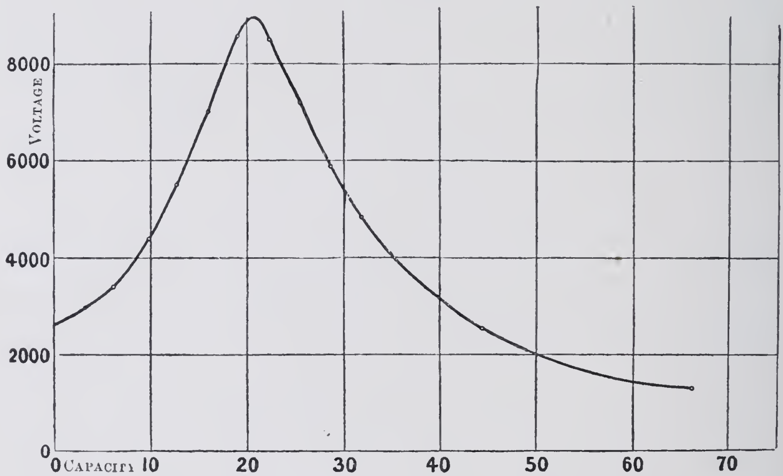


Fig. 15.—Variation of Terminal Voltage with Capacity in the Case of a Circuit having Capacity and Inductance when acted upon by a Periodic Electromotive Force.

frame being 1 meter in length. Let one circuit, P, have a Leyden jar or jars and spark gap associated with it, so as to form an oscillatory circuit. Let the other circuit, S, be placed at some little distance, and its ends joined by a small incandescent lamp. Then if oscillations be produced in the first circuit P by discharges of an induction coil, I, and if the second circuit be placed parallel to it and at no great distance, oscillations will be induced in this second circuit, and these, if the circuits are near enough, will cause the small glow lamp to be illuminated.

In this case we have what are called forced oscillations produced in the secondary circuit. If, however, we cut the secondary circuit S and introduce a condenser formed of a Leyden jar or jars, we can arrange such a capacity that the secondary circuit has the same oscillation constant as the primary. That is, for each circuit, P and S, the quantity $\sqrt{CL}$, where C is the capacity and L the inductance, has the same value.

When this is done we find that the inductive effect of the primary circuit on the secondary circuit is greatly increased, and that we can

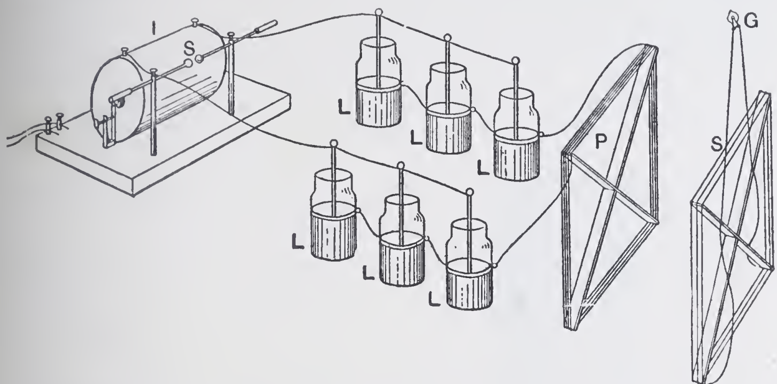


FIG. 16.—Production of Electric Oscillations in a Secondary Circuit assisted by Resonance. I, induction coil; L, L, Leyden jars; P, primary circuit; S, secondary circuit; G, incandescent lamp.

put the secondary circuit much farther off and yet light up the incandescent lamp in it to the same brilliancy. This increased effect is due to resonance. By making the oscillation constant of the primary and secondary circuits the same, we have "tuned" as it is called, the two circuits to each other, and the inductive effects are vastly enhanced.

We can in a similar manner exhibit the effects of resonance in connection with open circuits. Let a spiral of bare copper wire, ML (see Fig. 17), be wound in turns not touching each other round an ebonite or wooden frame or cylinder. An oscillatory circuit is then formed of a part, L, of this helix, and a condenser, C, and spark gap, S, excited by an induction coil, I, as usual. The point of contact a with the section of the spiral circuit which lies towards the middle of the helix must be capable of being shifted. The helix is

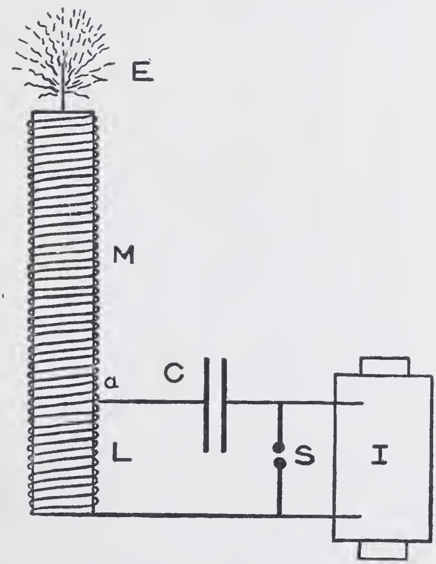


FIG. 17.—Resonance Helix.

then divided into two unequal parts, one part, L, is being employed as the inductance in an oscillatory circuit, and the other, M, is a free or open circuit in contact with this oscillatory circuit. If we set up

oscillations, and shift the point of contact a so as to lengthen or shorten the free part of the helix, we shall find such a position that a powerful electric brush, E, starts from the free end of the helix, showing that strong electric oscillations are being set up in it. This arrangement is much used for creating high frequency electric brush discharges as used in medical work. It is then known as an Oudin Resonator (see Fig. 18).

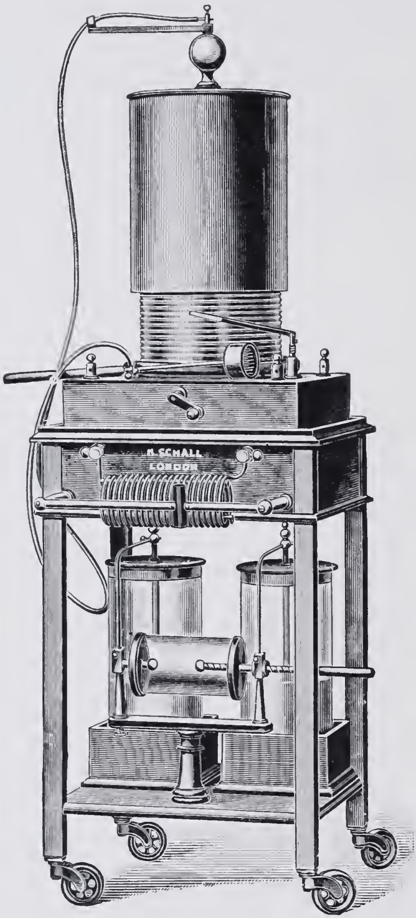


Fig. 18.—Oudin Resonator for creating High Frequency Electric Brush Discharges.

The above-described phenomena are called resonance effects, and two electric circuits so coupled together that oscillations in one act by induction to create oscillations in the other, constitute an *oscillation transformer*. We have, however, in this preliminary description, for the sake of simplicity, avoided reference to the reaction which one circuit exercises on the other. We cannot define more precisely what we mean by saying that two circuits are in resonance with each other, or tuned together or syntonized, until we have examined a little more in detail what really takes place in such cases.

The laws governing the action of oscillation transformers when very high frequency currents are employed differ greatly from those which hold good in the case of low frequency alternating current transformers. For example, if we desire to make a step-up transformer for raising potential when employing low frequency alternating currents, we should construct one in which the two coils had a very different number of turns, and a low electromotive force applied to the terminals of the coil of the smaller number of turns would be raised in value, so that the terminal potential difference of the two coils would be almost in the ratio of the number of their turns. In the case of high frequency oscillations, the ratio of transformation of potential is not in the proportion of the number of turns of the two circuits.

Before, however, we can discuss the theory of oscillation

transformers, it is necessary to explain briefly the simplest analytical method of dealing with problems in alternating currents.

10. The Representation of Alternating Currents by Complex Quantities.—The study of alternating current phenomena, and therefore also of electric oscillations, is assisted by the adoption of simple mathematical methods for representing the quantities with which we are concerned. The usual method of procedure is to express the instantaneous value of a periodic current or electromotive force as a function of the maximum value during the phase, and of the time expressed as a fraction of the complete periodic time. In actual practice we are chiefly concerned, however, with the maximum value, or with the root-mean-square value (R.M.S. value) of the periodic quantity during the period, and we can simplify the analytical treatment if we can avoid introducing the symbol for time.

The R.M.S. value of a periodic current or electromotive force is defined as follows:—

Let i be the value, say, of the current at any time, t, reckoned from the beginning of the period, and let T be the periodic time, then the R.M.S. value, J, is given by the expression—

$$\mathrm{J} = \sqrt{\frac{1}{T}\int_0^T i^2 dt}$$

Hence, if the quantity i varies in a simple harmonic manner, so that—

$$i = I \sin pt,$$

where I is the maximum value, then—

$$\mathrm{J} = \frac{I}{\sqrt{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (53)$$

We can always, therefore, determine J from I when the equation to the curve is given.

All we need, therefore, in discussing problems connected with simple periodic currents is to represent in some manner the phase or direction and maximum magnitude of the current or electromotive force.

This is most conveniently done by means of *complex quantities*.

If a denotes any line or vector of given length drawn horizontally and to the right, then with the usual convention $-a$ will denote an equal horizontal line to the left. Again, we may denote a line of the same length drawn vertically upwards by ja, and a line of the same length drawn vertically downwards by $-ja$. The quantity j is therefore an algebraic *sign of perpendicularity*. Since, as regards direction, $+a$ bears the same relation to ja that ja bears to $-a$, we have—

$$\frac{a}{ja} = \frac{ja}{-a}$$

It follows that $j^2 = -1$ or $j = \sqrt{-1}$, and j has the same analytical signification as $\sqrt{-1}$, viz. when applied as a multiplier or operator to a vector it turns it through a right angle.

Hence any line may be represented as the vector sum of two lines, consisting of a horizontal of a units in length and a vertical

component of b units in length. The proper representation of it is, therefore, $\pm a \pm jb$. The length or *size* of this line is $\sqrt{a^2 + b^2}$.

Quantities of the form $a + jb$ are called *complex quantities*, and $\sqrt{a^2 + b^2}$ is called the *modulus* of $a + jb$. The ratio $\frac{b}{a}$ is called the *slope* of the vector.

Hence lines or vectors may be drawn from any point to represent the maximum values of simple periodic quantities. The elements or steps a or b will represent the instantaneous values of these quantities, and their moduli will represent their actual measured maximum values, and if divided by $\sqrt{2}$ their R.M.S. values.

These complex quantities have certain properties, the chief of which may here be briefly mentioned. We shall take a single capital letter to represent a vector as a vector, and the same letter in brackets to represent its *size*.

Thus $\mathrm{E} = a + jb$ represents a *vector*, and $(\mathrm{E}) = \sqrt{a^2 + b^2}$ represents its *size*.

The reader should note and verify the following rules for dealing with these complex quantities and their moduli or size:—

(i.) Multiplication by j turns a vector through a right angle in a counter-clockwise or positive direction of rotation.

If $a + jb$ is any vector, then $j(a + jb) = -b + ja$ is a vector of the same size at right angles to $a + jb$.

(ii.) Multiplication by $-j$ turns a vector through a right angle in the clockwise direction.

If $a + jb$ is any vector, then $-j(a + jb) = (b - ja)$ is a vector of the same size at right angles negatively.

(iii.) If we denote the slope of the vector by θ, then $\frac{b}{a} = \tan\theta$, and if we denote the size of the vector by (A), then $a = (\mathrm{A})\cos\theta$ and $b = (\mathrm{A})\sin\theta$. Therefore $\mathrm{A} = (\mathrm{A})(\cos\theta + j\sin\theta)$.

The quantity $(\cos\theta + j\sin\theta)$ is called a *rotator*, for if applied to any vector it rotates it through an angle θ without changing its size.

Thus we can easily show, by multiplication and collection, that the size of the vector X, where $\mathrm{X} = (a + jb)(\cos\theta + j\sin\theta)$, is $\sqrt{a^2 + b^2}$.

It is the same as the size of the vector $a + jb = \mathrm{A}$.

The vector X, however, is turned through an angle θ in the positive direction, beyond the vector A. If we insert in the operator $(\cos\theta + j\sin\theta)$ the exponential values of sine and cosine, viz.—

$$\sin\theta = \frac{\epsilon^{j\theta} - \epsilon^{-j\theta}}{2j} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

$$\text{and} \quad \cos\theta = \frac{\epsilon^{j\theta} + \epsilon^{-j\theta}}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

$$\text{we have} \quad \cos\theta + j\sin\theta = \epsilon^{j\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (56)$$

Hence $\epsilon^{j\theta}$ and $\epsilon^{-j\theta}$ are also rotating operators, causing rotation of vectors through an angle θ in the positive or negative direction when applied to them.

If in place of θ we write pt, where t signifies time and $p = \frac{2\pi}{T}$,

T being the periodic time, we see that A $(\cos pt + j \sin pt) = A\epsilon^{jpt}$ signifies a vector of length (A) *continually rotating* round one extremity with an angular velocity p.

Additional important properties of complex quantities are as follows:—

(i.) If two complexes are multiplied together, the modulus or size of their product is the product of their separate moduli or sizes. Thus if $a + jb$ and $c + jd$ are two vectors, their sizes are $\sqrt{a^2 + b^2}$ and $\sqrt{c^2 + d^2}$. Also $(a + jb)(c + jd)$ is another vector, and its size is $\sqrt{a^2 + b^2} \cdot \sqrt{c^2 + d^2}$.

This is easily proved by multiplication and collection of terms.

(ii.) The same rule may be extended to quotients, powers, and roots of complex quantities. Accordingly, any such compound complex quantity as $\dfrac{a + jb}{c + jd}\sqrt{e + jf}$ may be written out in the canonical form $A + jB$, and its size $\sqrt{A^2 + B^2}$ determined.

We need not, however, take the trouble to make this calculation, because the size of the above vector can be written down at once by the above rule, for it is equal to—

$$\frac{\sqrt{a^2 + b^2}}{\sqrt{c^2 + d^2}}\sqrt{\sqrt{e^2 + f^2}}$$

Since a complex quantity represents a vector or line, it is obvious that if two complex quantities are equal, their horizontal and vertical steps or real and unreal parts must be respectively equal. Thus, if—

$$a + jb = c + jd$$

we must have $a = c$ and $b = d$.

A process continually required is that of separating a complex quantity into its real and unreal parts. Thus, if we have the complex equation—

$$\frac{a + jb}{c + jd}(e + jf) = i + jk$$

we can separate out the steps as follows: Multiply numerator and denominator by $c - jd$; we then have—

$$i + jk = \frac{aec - bfc + afd + ebd}{c^2 + d^2} + j\frac{acf + ebc + aed - bfd}{c^2 + d^2}$$

$$\text{Hence} \quad i = \frac{aec - bfc + afd + ebd}{c^2 + d^2}$$

$$\text{and} \quad k = \frac{acf + ebc + aed - bfd}{c^2 + d^2}$$

The above rules will afford the reader most of the information necessary to follow the application of complex quantities to the representation of simple periodic quantities.

This method consists in representing the maximum value of a simple harmonic electromotive force or current by a vector denoted by such a complex as $a + jb$. Then we fix its position in space

because the slope of the vector is such that $\frac{b}{a} = \tan\theta$, and its length or size by $\sqrt{a^2 + b^2}$. An expression such as $A\epsilon^{jpt}$ represents then a rotating vector and its real part, viz. A cos pt represents its instantaneous value or projection on a certain axis, and A represents the magnitude or size of its maximum value.

In connection with simple period quantities, a theorem of great utility is as follows: If A sin pt represents any simple harmonic quantity, and B cos pt represents another of different amplitude but the same frequency, then A sin pt + B cos pt also represents a simple periodic quantity of amplitude $\sqrt{A^2 + B^2}$, but differing in phase from the first, viz. A sin pt, by an angle ϕ, such that $\tan\phi = \frac{B}{A}$. Hence, $A \sin pt + B \cos pt = \sqrt{A^2 + B^2}\sin(pt + \phi)$.

To prove the theorem, divide both sides by $\sqrt{A^2 + B^2}$, then since $\sin\phi = \frac{B}{\sqrt{A^2 + B^2}}$ and $\cos\phi = \frac{A}{\sqrt{A^2 + B^2}}$, because $\tan\phi = \frac{B}{A}$, the identity is evident.

11. Theory of Coupled Oscillation Circuits having Capacity and Inductance in Series.—Let us consider two circuits, each having inductance, L, capacity, C, and resistance, R, and specify these quantities for the two circuits respectively by the suffixes 1 and 2. We shall follow first the lines of investigation in an interesting paper by A. Oberbeck.[29] Let these circuits be placed in inductive connection with each other by making the inductance in each circuit one of the coils of an oscillation transformer (see Fig. 19). Let these two circuits have a mutual inductance, M.

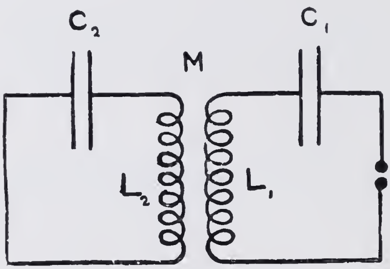


FIG. 19.—Two Coupled Oscillation Circuits.

Let oscillations be set up in one circuit. It is required to find the resulting currents in the two circuits and potential differences of the condenser plates, due to the mutual reaction of the circuits.

Let i_1 and i_2 be the currents at any instant, and v_1 and v_2 the potential differences of the condenser plates. Then we have the fundamental equations—

$$L_1\frac{di_1}{dt} + M\frac{di_2}{dt} + R_1 i_1 - v_1 = 0 \quad . \quad . \quad . \quad . \quad (57)$$

$$L_2\frac{di_2}{dt} + M\frac{di_1}{dt} + R_2 i_2 - v_2 = 0 \quad . \quad . \quad . \quad . \quad (58)$$

[29] See A. Oberbeck, "Ueber den Verlauf der Electrischen Schwingungen bei den Tesla'schen Versuchen," *Wied. Ann. der Physik*, 1895, vol. 55, p. 623. See also G. W. Pierce, "On Experiments on Resonance in Wireless Telegraph Circuits," *Physical Review*, vol. 24, February, 1902, p. 152.

If we differentiate each equation with respect to time, and remember that—

$$i_1 = -C_1\frac{dv_1}{dt},\ i_2 = -C_2\frac{dv_2}{dt} \quad . \quad . \quad . \quad . \quad (59)$$

we arrive at the equations—

$$C_1L_1\frac{d^2i_1}{dt^2} + C_1R_1\frac{di_1}{dt} + C_1M\frac{d^2i_2}{dt^2} + i_1 = 0 \quad . \quad . \quad . \quad (60)$$

$$C_2L_2\frac{d^2i_2}{dt^2} + C_2R_2\frac{di_2}{dt} + C_2M\frac{d^2i_1}{dt^2} + i_2 = 0 \quad . \quad . \quad . \quad (61)$$

By differentiating the last equations twice, and eliminating between the results and the originals, we can separate the variables and obtain the equation—

$$C_1C_2(L_1L_2 - M^2)\frac{d^4i_1}{dt^4} + C_1C_2(R_1L_2 + R_2L_1)\frac{d^3i_1}{dt^3}$$
$$+(C_2L_2+C_1L_1+C_1C_2R_1R_2)\frac{d^2i_1}{dt^2} + (C_1R_1+C_2R_2)\frac{di_1}{dt} + i_1=0 \quad (62)$$

and a similar one in i_2.

In nearly all cases with which we are concerned in radiotelegraphy, the resistance of the oscillatory circuits is small compared with their reactance, and hence we shall not commit sensible error by neglecting the terms involving R_1 and R_2 in the above equations.

If also we write k^2 for $\frac{M^2}{L_1L_2}$ where k is called the *coefficient of coupling*, and assume that the currents vary in a simple harmonic manner, we may assume that both i_1 and i_2 are quantities which vary as the real part of ϵ^{jpt} where $j = \sqrt{-1}$.

$$\text{Hence} \quad \frac{d^2i_1}{dt^2} = -p^2i_1 \quad \text{and} \quad \frac{d^4i_1}{dt^4} = p^4i_1$$

Making these substitutions, the equation (62) reduces to—

$$C_1L_1C_2L_2(1 - k^2)p^4 - (C_1L_1 + C_2L_2)p^2 + 1 = 0 \quad . \quad (63)$$

Now the natural time period T_1 of one circuit taken alone is such that $T_1^2 = 4\pi^2C_1L_1$, and that of the other, T_2, is given by $T_2^2 = 4\pi^2C_2L_2$, and the quantity p in equation (63) denotes 2π divided by the frequency or frequencies of the circuits when coupled together. If we write $\frac{4\pi^2}{T^2}$ for p^2 in the equation (62), and substitute for C_1L_1 and C_2L_2 their equivalents as above, we obtain the following biquadratic in T, viz.—

$$T^4 - (T_1^2 + T_2^2)T^2 + T_1^2T_2^2(1 - k^2) = 0 \quad . \quad . \quad . \quad (64)$$

The solution of which is—

$$T^2 = \frac{T_1^2 + T_2^2 \pm \sqrt{(T_1^2 - T_2^2)^2 + 4k^2T_1^2T_2^2}}{2} \quad . \quad . \quad (65)$$

Hence it is clear there are two values of T corresponding to the two roots of the equation, and this signifies that when the oscillatory circuits are coupled together so as to act inductively on each other, then oscillations are set up in each circuit of two periods differing

from each other, and from the natural free periods T_1 and T_2 of each circuit taken separately. Let us call the time periods of these two oscillations T' and T'', then we have—

$$T' = \sqrt{\frac{T_1^2 + T_2^2 + \sqrt{(T_1^2 - T_2^2)^2 + 4k^2T_1^2T_2^2}}{2}} \quad . \quad (66)$$

$$T'' = \sqrt{\frac{T_1^2 + T_2^2 - \sqrt{(T_1^2 - T_2^2)^2 + 4k^2T_1^2T_2^2}}{2}} \quad . \quad (67)$$

Several cases of interest then present themselves.

I. Let $T_1 = T_2$, that is, let two circuits be supposed to have the same periodic time when separated far apart from each other. This is the case of *isochronism*, or, as it is usually called, of *resonance*. If, then, in (66) and (67) we put $T_1 = T_2 = T$, we have—

$$T' = T\sqrt{1+k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (68)$$

$$T'' = T\sqrt{1-k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (69)$$

or if we consider frequencies n' and n'' and n instead of time periods, we have—

$$n' = \frac{n}{\sqrt{1+k}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (70)$$

$$n'' = \frac{n}{\sqrt{1-k}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

from which we have—

$$k = \frac{n''^2 - n'^2}{n''^2 + n'^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (72)$$

II. If the circuits are in resonance, that is, if $T_1 = T_2 = T$, and if the coefficient k is zero or extremely small, then we have $T' = T'' = T$. In other words, there are oscillations of only one frequency set up in each circuit. This is the case if the circuits are far apart or *feebly coupled.*

III. If the circuits are in resonance, but closely coupled or near together, so that the coefficient $k = 1$, we have $T' = \sqrt{T_1^2 + T_2^2}$ and $T'' = 0$. Hence, in this case also there are oscillations of only one periodicity, which is the square root of the sum of the squares of the periodic times of the two circuits when far apart.

We have in the next place to consider the transformation ratio of an oscillation transformer connecting two circuits having inductance and capacity. We shall assume that the resistances of the circuits, and therefore the damping, to be negligible, and we can then write the equations (57) and (58) when the values of i_1 and i_2 given in (59) are substituted, in the form—

$$C_1L_1\frac{d^2v_1}{dt^2} + C_2M\frac{d^2v_2}{dt^2} + v_1 = 0 \quad . \quad . \quad . \quad . \quad (73)$$

$$C_2L_2\frac{d^2v_2}{dt^2} + C_1M\frac{d^2v_1}{dt^2} + v_2 = 0 \quad . \quad . \quad . \quad . \quad (74)$$

By differentiating the above equations twice with regard to t and

eliminating between the resulting and original equations, we arrive at two other equations, viz.—

$$C_1C_2(L_1L_2 - M^2)\frac{d^4v_1}{dt^4} + (C_1L_1 + C_2L_2)\frac{d^2v_1}{dt^2} + v_1 = 0 \quad . \quad (75)$$

and a similar equation in v_2.

These equations have particular solutions of the form—

$$v_1 = A_1 \cos p_1t + B_1 \cos p_2t \quad . \quad . \quad . \quad . \quad . \quad (76)$$

$$v_2 = A_2 \cos p_1t + B_2 \cos p_2t \quad . \quad . \quad . \quad . \quad . \quad (77)$$

This may be proved by differentiating (76) and (77) and substituting in the original equations (73), (74), and (75) which they will be found to satisfy.

Since v_1 is a simple periodic quantity it may be represented by the real part of $\epsilon^{jpt} = \cos pt + j \sin pt$, and then we have—

$$\frac{d^4v_1}{dt^4} = p^4v_1 \quad \text{and} \quad \frac{d^2v_1}{dt^2} = - p^2v_1$$

Hence, substituting these values in (75), we obtain a biquadratic in p, viz.—

$$p^4 + \frac{C_1L_1 + C_2L_2}{C_1C_2(L_1L_2 - M^2)}p^2 + \frac{1}{C_1C_2(L_1L_2 - M^2)} = 0 \quad . \quad (78)$$

If the roots of this are p_1^2 and p_2^2, we have then—

$$p_1^2 + p_2^2 = \frac{C_1L_1 + C_2L_2}{C_1C_2(L_1L_2 - M^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (79)$$

$$p_1^2p_2^2 = \frac{1}{C_1C_2(L_1L_2 - M^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (80)$$

and hence $$p_1^2 - p_2^2 = \frac{\sqrt{(C_1L_1 - C_2L_2)^2 + 4C_1C_2M^2}}{C_1C_2(L_1L_2 - M^2)} \quad . \quad . \quad (81)$$

From (76) and (77) find the values of $\frac{d^2v_1}{dt^2}$ and $\frac{d^2v_2}{dt^2}$ and substitute in the original equations (73) and (74), and we find that—

$$\left.\begin{aligned} \frac{A_1}{A_2} &= \frac{p_1^2MC_2}{1 - p_1^2L_1C_1} \\ \frac{B_1}{B_2} &= \frac{p_2^2MC_2}{1 - p_2^2L_1C_1} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (82)$$

Let V_1 be the maximum potential difference of the plates of the primary condenser, viz. the discharge potential. Hence, when $t = 0$, $v_1 = V_1$ and $v_2 = 0$. Let V_2 be the maximum potential difference of the plates of the secondary condenser. Then we have at the instant $t = 0$—

$$A_1 + B_1 = V_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (83)$$

$$A_2 + B_2 = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (84)$$

For shortness, put $\frac{A_2}{A_1} = a_1$ and $\frac{B_2}{B_1} = a_2$. Then it is obvious that—

$$\left.\begin{aligned} A_1 &= \frac{V_1 a_2}{a_2 - a_1} & B_1 &= -\frac{V_1 a_1}{a_2 - a_1} \\ A_2 &= \frac{V_1 a_1 a_2}{a_2 - a_1} & B_2 &= -\frac{V\, a_1 a_2}{a_2 - a_1} \end{aligned}\right\} \quad . \quad . \quad . \quad (85)$$

The solutions of (73) and (74) are then—

$$v_1 = \frac{V_1}{a_2 - a_1}(a_2 \cos p_1 t - a_1 \cos p_2 t) \quad . \quad . \quad . \quad (86)$$

$$v_2 = \frac{V_1 a_1 a_2}{a_2 - a_1}(\cos p_1 t - \cos p_2 t) \quad . \quad . \quad . \quad . \quad (87)$$

and $$V_2 = V_1 \frac{a_2 a_1}{a_2 - a_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (88)$$

In this last expression insert the proper values of a_1 and a_2 from (82), and we have—

$$V_2 = V_1 \frac{MC_1}{\sqrt{(L_1C_1 - L_2C_2)^2 + 4M^2C_1C_2}} \quad . \quad . \quad . \quad (89)$$

Accordingly, when the circuits are syntonized, that is, when $C_1L_1 = C_2L_2$, we have—

$$V_2 = V_1 \frac{\sqrt{C_1}}{2\sqrt{C_2}}$$

Hence the transformation ratio in this case depends only on the relative capacity of the condensers in the primary and secondary circuits.

We have then for the potential difference v_2 of the terminals of the secondary condenser at any instant the expression—

$$v_2 = V_1 \frac{\sqrt{C_1}}{2\sqrt{C_2}}(\cos p_1 t - \cos p_2 t) \quad . \quad . \quad . \quad . \quad (90)$$

and for the secondary current i_2 the equation—

$$i_2 = \frac{V_1}{2}\sqrt{C_1C_2}(p_2 \sin p_2 t - p_1 \sin p_1 t)$$

From (79) and (81) it can be shown that when the circuits are syntonized so that $C_1L_1 = C^2L^2 = CL = \frac{1}{p^2}$, where $\frac{2\pi}{p}$ is the natural time period of each circuit, we have—

$$p_1 = \frac{p}{\sqrt{1 + k}} \text{ and } p_2 = \frac{p}{\sqrt{1 - k}} \quad . \quad . \quad . \quad . \quad (91)$$

where $$k = \frac{M}{\sqrt{L_1L_2}}$$

Accordingly, the secondary current i_2 is then the sum of two currents of different frequency and amplitude, for—

$$i_2 = \frac{V_1}{2}\sqrt{C_1C_2}\frac{p}{\sqrt{1-k}} \sin \frac{p}{\sqrt{1-k}}t - \frac{V_1}{2}\sqrt{C_1C_2}\frac{p}{\sqrt{1+k}} \sin \frac{p}{\sqrt{1+k}}t$$

The oscillation of greatest frequency has also the greatest amplitude.

If the circuits are not syntonized, then—

$$V_2 = V_1 \frac{kC_1\sqrt{L_1L_2}}{\sqrt{(C_1L_1 - C_2L_2)^2 + 4k^2C_1L_1C_2L_2}} \quad . \quad . \quad . \quad (92)$$

And if $k = 1$ or $M = \sqrt{L_1L_2}$, the above becomes—

$$\frac{V_1}{V_2} = \frac{\sqrt{L_1}}{\sqrt{L_2}} + \frac{C_2\sqrt{L_2}}{C_1\sqrt{L_1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (93)$$

The second term on the right-hand side may in some cases be negligible compared with the first, and then if N_1 and N_2 are the numbers of turns on the primary and secondary circuits of the oscillation transformer, we have—

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (94)$$

We see, therefore, that in the case of the oscillation transformer, with its two circuits loosely coupled and tuned in resonance, the damping being negligible, the ratio of transformation is determined solely by the capacities in the two circuits; whereas when the circuits are not tuned, but closely coupled, the ratio is determined by the relative number of turns on the two circuits.

The discussion of the more general case in which the damping of the two circuits is not negligible leads to greater analytical difficulties, and is dealt with in the subsequent sections.

Accordingly, the design of an oscillation transformer to transform high frequency currents is based on very different facts to the design of low frequency transformers. In the latter case the transformer changes terminal voltage almost in the ratio of the numbers of turns on the two circuits. In the former case, if the circuits are of equal time period separately, the change ratio depends solely on the capacities in the two circuits.

By making the primary capacity sufficiently large compared with the secondary capacity, we can increase in the same proportion the terminal voltages of the two condensers. In this case there are two periods of oscillation in the coupled circuit, the mean of the squares of the two periodic times being equal to the square of the common time period. The two may, however, become equal when the coupling is sufficiently loose.

The other case of a pair of closely coupled circuits, with different time periods, presents us with an instance of forced oscillations. The single resultant forced time period has a square equal to the sum of the squares of the time periods of the two circuits separately.

Following the investigation of Oberbeck (*loc. cit.*), we may give a numerical example which will illustrate the foregoing.

Let there be two coupled circuits having capacity, inductance, and mutual inductance.

Let $L_1 = 1000$ cms., $L_2 = 25{,}000$ cms., $M = 3000$ cms.; also let $C_1 = 0{\cdot}001$ mfd. $= 10^{-18}$ electromagnetic units, and let $C_2 = 0{\cdot}00004$ mfd. $= 0{\cdot}04 \times 10^{-18}$ electromagnetic units.

$$\text{Then} \quad L_1C_1 = L_2C_2 = 10^{-15}$$

$$\text{Therefore} \quad T_1 = T_2 = 2\pi\sqrt{L_1C_1} = T$$

$$\text{or} \quad T^2 = \frac{4\pi^2 10}{10^{16}}$$

$$\text{Also} \quad \theta^2 = 4\pi^2 M\sqrt{C_1C_2} = \frac{4\pi^2 6}{10^{16}}$$

$$\text{Accordingly} \quad T'' = 2\pi\frac{4}{10^8} \text{ and } T''' = 2\pi\frac{2}{10^8}$$

Hence the two frequencies n_1 and n_2 are $n_1 = \frac{10^8}{25{\cdot}132}$ and $n_2 = \frac{10^8}{12{\cdot}566}$, whilst the common frequency $= n_0 = \frac{10^8}{19{\cdot}844}$, this last being the frequency which would exist in each circuit if they were separate and far apart.

It is important that the reader should fully understand the reason for the appearance of these two oscillations of different frequencies in syntonic coupled isochronous circuits. An assistance may be obtained by referring again to the experiment with the two equal pendulums hung on a loose string, to which reference was made in § 9 of this chapter.

Consider, then, the case of these two equal pendulums. Each has the same time period when vibrating alone. If, however, they are hung side by side on a loose string, we have seen that when one pendulum is set in motion it imparts its motion to the other little by little, and in so doing brings itself to rest. Then the second pendulum in turn gives back its motion to the first, and so on. It is clear, then, that when either of the two pendulums is the driven pendulum, it must have its natural period of vibration increased, because it is being accelerated; whereas when it is the driving pendulum it must have its natural period of vibration reduced, because it is being retarded. Hence, in the compound system, two rates of oscillation must be present, one greater and one less than the natural equal common period of the two pendulums separately.

The same thing happens with two tuning-forks, and also with two isochronous coupled electric oscillatory circuits. In this last case, owing to the mutual inductance, adjuvant and counter-electromotive forces are alternately introduced into each circuit, which create the two frequencies of oscillation theoretically and experimentally found.

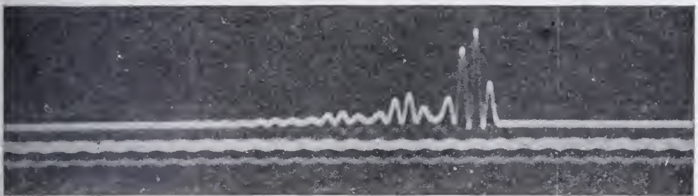
This has been well shown by experiments made by Dr. E. Taylor-Jones in investigations made especially for the purpose of recording the oscillations in a coupled circuit photographically.[30] He employed an electrostatic oscillograph of his own design as a means of delineating the oscillations.[31]

He used two circuits with the following constants. The secondary circuit was the secondary coil of an induction coil, having an inductance of $70{\cdot}15 \times 10^9$ cms. or 70·15 henrys, and its resistance was

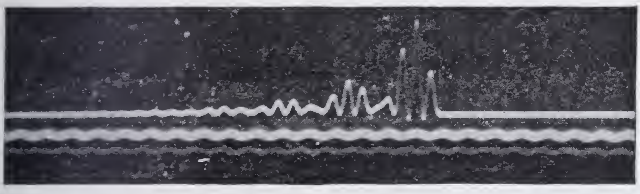
[30] See E. Taylor-Jones, "Electrical Oscillations in Complex Circuits," *Phil. Mag.*, January, 1909.

[31] "A Short-Period Electrometer," *Phil. Mag.*, August, 1907.

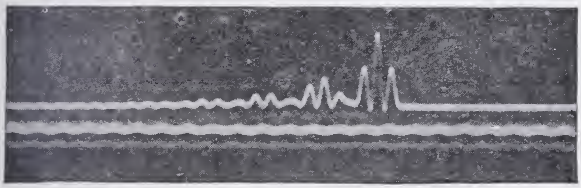
14,022 ohms. The primary circuit consisted of 1200 turns of No. 14 copper wire wound on a glass tube. Its resistance was 1·0378 ohms,



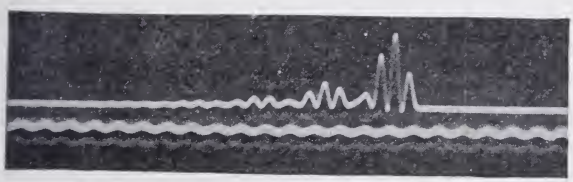
$C_1 = 9·55$ mfds. $C_2 = 0·000875$ mfd.
$L_1 = 4·62$ millihenrys. $L_2 = 70·15$ henrys.
$k = 0·385$.



$C_1 = 11·87$ mfds. $C_2 = 0·001063$ mfd.
L_1, L_2, and k, same as above.



$C_1 = 9·55$ mfds. $C_2 = 0·001063$ mfd.
L_1, L_2, and k, same as above.



$C_1 = 11·87$ mfds. $C_2 = 0·000875$ mfd.
L_1, L_2, and k, same as above.

FIG. 20.—Oscillograms of Oscillations in Coupled Circuits. (Taylor-Jones.)

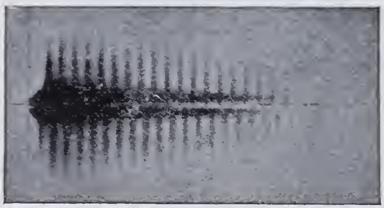
and inductance 4,619,000 cms. or 4·619 millihenrys. The coefficient of coupling of these circuits was such that $k = 0·1483$ or $k = 0·385$.

Hence the circuits were somewhat closely coupled. The capacity in the primary circuit was of the order of 10 mfds., and that in the secondary about 0·001 mfd.

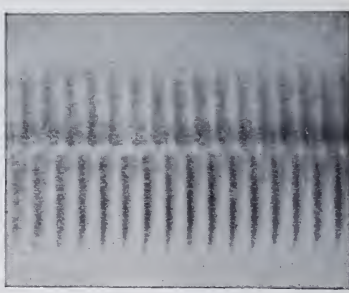
The frequencies n_1 and n_2 were calculated from Oberbeck's formula as given in equation (65).

These frequencies were of the order of 500 to 1000 per second. The resultant oscillation or potential difference of the secondary condenser was then recorded photographically, and is shown in the series of curves given in Fig. 20. These show very admirably the existence of the "beats" in the damped oscillation due to the co-existence of oscillations of two frequencies in the resultant oscillation. The same was proved to be the case when persistent oscillations were employed produced by a Duddell musical core instead of the damped oscillations due to a condenser discharge.

A confirmation of the above autographic delineation of the resultant oscillation in a coupled circuit is given by the experiments



(*a*)



(*b*)

Fig. 21.

(*a*) Oscillogram of Damped Oscillations in a Single or Uncoupled Circuit. (Dieselhorst.)

(*b*) Oscillogram of Undamped Oscillations in a Single or Uncoupled Circuit. (Dieselhorst.)

of Dr. Dieselhorst with the oscillograph vacuum tube described in Chap. I., § 6. Making use of this, Dr. Dieselhorst photographed the damped oscillations of a condenser discharge, and obtained the photograph shown in Fig. 21 (*a*), in which the decadent amplitude of the black shaded lines represents the gradual damping out of the oscillations. When, however, this condenser circuit was coupled electromagnetically to a radiating and tuned antenna, so that it became one member of a pair of coupled circuits, the oscillograph photograph was as shown in Fig. 22, in which the black lines representing the oscillations are separated into bunches, and these interspaces correspond to the beats and show that there must have been two superimposed oscillations.[32]

A photograph taken by the same means with an uncoupled or single oscillatory circuit in which persistent oscillations exist is shown in Fig. 21 (*b*).

A most complete experimental investigation of this subject has been made by Professor George W. Pierce.[33] He arranged two

[32] See *Electrical Engineering*, April 23, 1908, p. 625.

[33] See Prof. G. W. Pierce, "Experiments on Resonance in Wireless Telegraph Circuits," Part V. The *Physical Review*, vol. xxiv. p. 166, February, 1907.

coupled circuits, each having capacity and inductance and set up in arc oscillations by means of a spark gap and induction coil. The periodicity of the oscillations set up in the two circuits was then measured by making them act inductively upon a tertiary circuit very loosely coupled with the primary or secondary circuit. This tertiary circuit could have its inductance and capacity varied, and the condition in which the current induced in it had its maximum value was indicated by the deflection of a high frequency dynamometer or modified form of Fleming alternating current galvanometer.[34]

By calibrating this third circuit so that, in any condition of adjustment, the product of its inductance L and capacity C is known, we know its natural frequency n because $n = \frac{1}{2\pi\sqrt{CL}}$.

This circuit therefore becomes a means of measuring the frequency of the oscillations set up in the primary or secondary circuit by tuning the tertiary circuit first to one frequency and then to the other, and judging of this agreement by the fact that the tertiary current reaches a maximum or sub-maximum corresponding to that setting or to resonance between it and the other circuit for that frequency.

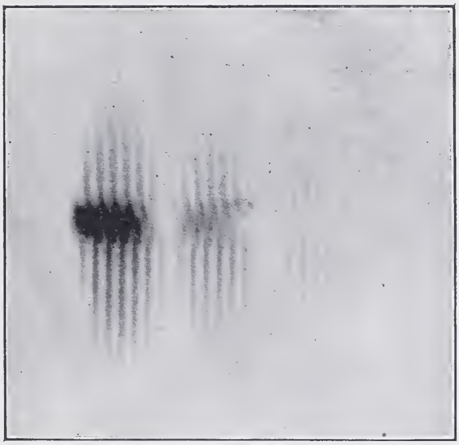


Fig. 22.—Oscillogram of Damped Oscillations in a Pair of Coupled Circuits. (Hans Boas.)

It will be shown in a later chapter that when oscillations are set up on a circuit some of the energy is radiated in the form of electro-magnetic waves, and the wave length λ of these waves is numerically equal to the product of their tune period T and the wave velocity u all measured in consistent units.

Hence in the expressions already given (66) and (67) for the time periods T_1 and T_2 of the two oscillations in coupled circuits, we may substitute λ_1 and λ_2 for the two wave lengths, and arrive at the expressions—

$$\lambda_1' = \sqrt{\frac{\lambda_1^2 + \lambda_2^2 + \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4k^2\lambda_1^2\lambda_2^2}}{2}} \quad . \quad . \quad (95)$$

$$\lambda_2' = \sqrt{\frac{\lambda_1^2 + \lambda_2^2 - \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4k^2\lambda_1^2\lambda_2^2}}{2}} \quad . \quad . \quad (96)$$

Professor Pierce measured carefully the wave-lengths of the waves set up in the two coupled circuits which he used, and compared

[34] See Chap. II. § 13.

the results with the above formulæ and found a very good agreement. The natural wave-length λ_2 of the secondary circuit was kept constant and equal to 1060 metres, whilst the primary circuit was varied so as to alter its natural wave-length λ_1 from 210 to 1560 metres. The observed and calculated values of λ_1' and λ_2' are set out in the following Table, and delineated in the curves in Fig. 23.

Calculated and observed wave-lengths radiated by a coupled oscillator. Circuits not syntonized. Primary capacity = 0·00432 mfd. Secondary capacity = 0·00482. Primary inductance, varied as below. Secondary inductance = 0·066 millihenry. Primary wave-length, varied as below. Secondary wave-length λ_2 = 1060 metres.

Pr. inductance.	Pr. wave-length.	Wave-lengths calculated.		Wave-lengths observed.	
Millihenrys.	Metres.	λ_1'	λ_2'	λ_1'	λ_2'
0·1585	1560	1740	727	—	710
0·139	1460	1670	712	1650	685
0·118	1350	1567	686	1570	665
0·10	1230	1462	680	1480	660
0·082	1130	1390	660	1370	660
0·065	1000	1273	685	1280	660
0·0482	870	1185	680	1185	630
0·0315	700	1127	595	1125	565
0·0172	510	1080	467	1090	460

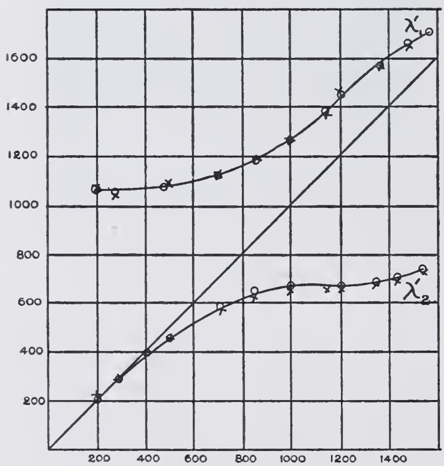


Fig. 23.

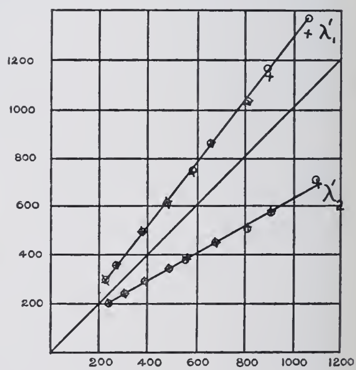


Fig. 24.

The agreement between observation and theory is fairly close.

Another series of observations was taken when the two coupled circuits had the same periodic time or wave-length when separated. This was the case of resonance.

In this case we have—

$$(\lambda_1')^2 = \lambda_1^2(1 + k) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (97)$$

$$(\lambda_2')^2 = \lambda_2^2(1 - k) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (98)$$

The results of observation are recorded in the Table on p. 271, and delineated in Fig. 24.

The convergence of the lines in Fig. 24, the ordinates of which represent the various values of λ_1' and λ_2', as the coupling becomes looser is very striking and in accordance with theory.

Calculated and observed wave-lengths radiated by a coupled oscillator with circuits syntonized to a common wave-length λ which was varied.

Natural free wave-length of either circuit.	Wave-lengths radiated from the coupled circuits.			
	Observed.		Calculated.	
λ	λ_1'	λ_2'	λ_1'	λ_2'
1060	1290	655	1335	680
900	1095	555	1150	555
810	1025	503	1032	507
690	860	450	870	440
570	700	380	714	374
487	600	330	609	322
395	480	280	485	278
290	345	224	352	210
252	275	204	294	174

12. The Damping in Coupled Circuits.—Oberbeck shows (*loc. cit.*) how to calculate the damping in each of the two coupled circuits forming an oscillation transformer when the resistances are not negligible. On referring to equation (64) in § 6, we see the value of p is given by an equation of the fourth degree of the form—

$$p^4 + fp^3 + gp^2 + hp^2 + k = 0 \quad . \quad . \quad . \quad . \quad (99)$$

The roots of this equation are—

$$(-\alpha + j\beta), \quad (-\alpha - j\beta), \quad (-\gamma + j\eta), \quad (-\gamma - j\eta)$$

Let α be small compared with β, and γ small compared with η, as is always the case in practice. Then Oberbeck proves that—

$$\alpha = \frac{f\beta^2 - h}{2(2\beta^2 - g)}, \qquad \gamma = \frac{f\eta^2 - h}{2(2\eta^2 - g)} \quad . \quad . \quad . \quad (100)$$

Let the coefficient of coupling $= \dfrac{M}{\sqrt{L_1L_2}}$ be denoted by k, and let us consider the case in which $L_1C_1 = L_2C_2$. Then if R_1 and R_2 are the resistances of the two circuits, Oberbeck shows that—

$$\alpha = \frac{\dfrac{R_1}{L_1} + \dfrac{R_2}{L_2}}{4(1+k)}, \qquad \gamma = \frac{\dfrac{R_1}{L_1} + \dfrac{R_2}{L_2}}{4(1-k)} \quad . \quad . \quad . \quad . \quad (101)$$

Hence the two oscillations resulting in the coupled circuits of equal separate period are differently damped. One is more damped and the other less damped than the mean of the damping in the two separate circuits.

If we write α_1 for $\dfrac{R_1}{2L_1}$ and α_2 for $\dfrac{R_2}{2L_2}$, then we have—

$$(1 + k)\alpha = \tfrac{1}{2}(\alpha_1 + \alpha_2)$$
$$(1 - k)\gamma = \tfrac{1}{2}(\alpha_1 + \alpha_2) \quad . \quad . \quad . \quad . \quad . \quad (102)$$

We see, therefore, that if $k = 0$, $\alpha = \gamma = \frac{1}{2}(\alpha_1 + \alpha_2)$, but if k is not zero then we have $\alpha < \gamma$.

13. General Theory of Resonance.—When two circuits having inductance, resistance, and capacity are inductively connected together, we are then presented with a unique case to consider if their natural time periods of oscillation when separate are the same. Oscillations in one circuit then create a strong response in the other coupled circuit. In practice we find that this *syntony* or agreement between the time periods of the two circuits must be very exact if the phenomenon of resonance is to take place. Hence any treatment of the subject would be incomplete which did not include an examination of the manner in which a departure from equality in the free time periods of the two circuits affects the result. We shall first consider the case of a secondary circuit which has an induced electromotive force created in it by a *sustained or continuous* simple periodic current in an adjacent primary circuit. Let C be the capacity in the secondary circuit, L the inductance, and R the resistance. Let the current in the circuit at any time, t, be denoted by i, and the potential difference of the terminals of the condenser by v. Let the damping factor $\frac{R}{2L}$ be denoted by α, and the logarithmic decrement by δ.

The condenser circuit has a natural time period of oscillation n_2, which is determined by the equation—

$$n_2 = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

Hence, if $p = 2\pi n_2$ and $\alpha = \frac{R}{2L}$, we have—

$$\frac{1}{LC} = p^2 + \alpha^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (103)$$

The differential equation for the current in the condenser circuit is—

$$L\frac{di}{dt} + Ri + v = e \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (104)$$

where $e = E \sin qt$ is the simple harmonic electromotive force acting in the secondary circuit due to the action of the current in primary circuit having a frequency n_1 such that $2\pi n_1 = q$.

Again, $i = C\frac{dv}{dt}$, and therefore, by substitution in (104), we have—

$$CL\frac{d^2v}{dt^2} + CR\frac{dv}{dt} + v = E \sin qt \quad . \quad . \quad . \quad (105)$$

To solve this last equation, differentiate it twice with respect to t, and eliminate sin qt with the aid of the original equation. We have then—

$$\frac{d^4v}{dt^4} + 2\alpha\frac{d^3v}{dt^3} + (p^2 + \alpha^2 + q^2)\frac{d^2v}{dt^2} + 2q^2\alpha\frac{dv}{dt} + q^2(p^2 + \alpha^2)v = 0$$

The auxiliary biquadratic of the above (see Boole's "Differential Equations," p. 194) is $(m^2 + q^2)(m^2 + 2\alpha m + p^2 + \alpha^2) = 0$, and the roots of this equation are—

$$m = \pm\sqrt{-1}\,q$$
$$m = -\alpha \pm \sqrt{-1}\,p$$

Hence the solution of (105) is—

$$v = \mathrm{P}\sin qt + \mathrm{Q}\cos qt + \mathrm{A}\epsilon^{-\alpha t}\sin pt + \mathrm{B}\epsilon^{-\alpha t}\cos pt$$

$$\text{or}\quad v = \mathrm{V}\sin(qt - \phi) + \mathrm{V}'\epsilon^{-\alpha t}\sin(pt - \theta) \quad . \quad . \quad . \quad . \quad (106)$$

where P, Q, A, and B are some constants such that $\mathrm{V} = \sqrt{\mathrm{P}^2 + \mathrm{Q}^2}$ and $\mathrm{V}' = \sqrt{\mathrm{A}^2 + \mathrm{B}^2}$.

This last solution indicates that the current in the secondary circuit consists of two superimposed oscillations.

(i.) A *forced oscillation* of amplitude V, which is undamped and has a frequency n_2 identical with that or the applied electromotive force.

(ii.) A *free natural oscillation*, having an initial maximum value V′, which is damped, and therefore dies out before long, leaving only the forced oscillation to persist.

If we differentiate (106) twice, and substitute the results in the original equation (105), we can neglect those terms which have a factor $\epsilon^{-\alpha t}$, as they die away after a short time, and we are then left with the equation—

$$\frac{\mathrm{E}}{\mathrm{CL}}\sin qt = \mathrm{V}(p^2 - q^2 + \alpha^2)\sin(qt - \phi) + \mathrm{V}2q\alpha\cos(qt + \phi)$$

$$\text{or}\quad \frac{\mathrm{E}}{\mathrm{CL}}\sin qt = \mathrm{V}\sqrt{(p^2 - q^2 + \alpha^2)^2 + (2q\alpha)^2}\sin(qt - \phi - \psi)$$

$$\text{Hence}\quad \mathrm{V} = \frac{p^2 + \alpha^2}{\sqrt{[(q^2 - p^2) - \alpha^2]^2 + [2q\alpha]^2}}.\mathrm{E}\quad . \quad . \quad . \quad . \quad (107)$$

and since the maximum value of the condenser current $I = \mathrm{CV}q$, we have an expression for the maximum value of the condenser current, viz.—

$$I = \frac{q}{\mathrm{L}\sqrt{[(q^2 - p^2) - \alpha^2]^2 + [2q\alpha]^2}}.\mathrm{E}\quad . \quad . \quad . \quad (108)$$

Suppose that α is small, so that α^2 is negligible in comparison with p^2. In this case the secondary circuit is said to be feebly damped. Then, bearing in mind that $\frac{p}{q} = \frac{n_2}{n_1} = x$, we may write the equation (108) for the current in the condenser circuit in the form—

$$I = \frac{\mathrm{E}}{\mathrm{L}\sqrt{q^2(1 - x^2)^2 + 4\alpha^2}}\quad . \quad . \quad . \quad . \quad . \quad (109)$$

where $q = 2\pi n$, $2\alpha = \frac{\mathrm{R}}{\mathrm{L}}$, and $x = \frac{n_2}{n_1}$.

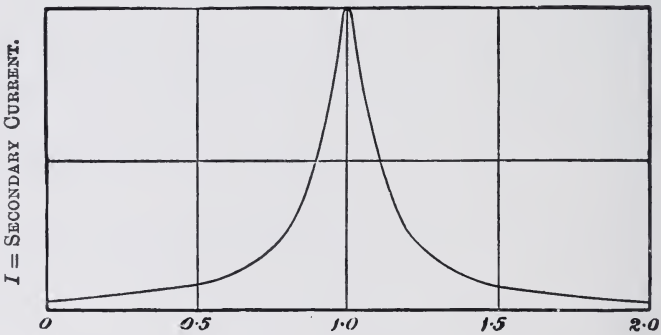
Let us examine the manner in which the current I varies as the ratio $\frac{n_2}{n_1}$ of the natural frequencies of the driving and driven circuits approximates to unity.

$$\text{Let } x = \frac{n_2}{n_1} = 0 \qquad \text{then } I = \frac{\mathrm{E}}{\mathrm{L}\sqrt{q^2 + (2a)^2}}$$

$$\text{when } x = \frac{n_2}{n_1} = 1 \qquad \text{then } I = \frac{\mathrm{E}}{2a\mathrm{L}} = \frac{\mathrm{E}}{\mathrm{R}}$$

$$\text{and if } x = \frac{n_2}{n_1} = \infty \qquad \text{then } I = 0$$

We see, therefore, that the expression for the current in the secondary circuit, considered as a function of the ratio of the natural frequencies of the two circuits, has a maximum value when $n_1 = n_2$. If we delineate the expression for I in the form of a curve, the abscissæ of which represents to scale $\frac{n_2}{n_1}$ and the ordinates the corresponding values of I, then we have a curve as shown in Fig. 25, which is called a *resonance curve*. This curve runs up into a peak



$\frac{n_2}{n_1}$ = Ratio of Frequencies.

Fig. 25.—A Resonance Curve.

very sharply, because the value of I depends on the difference of the squares of two quantities which are approaching each other in value. The current corresponding to equality in the frequency of the two circuits is called the *resonance current*. We shall denote it by I_r.

It is obvious that the ratio of the current corresponding to any particular value of $\frac{n_2}{n_1}$ not far from unity, to the current which exists when $\frac{n_2}{n_1}$ is unity, is given by the equation—

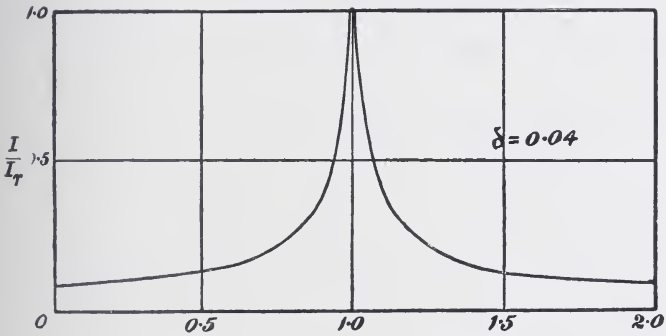
$$y = \frac{I}{I_r} = \frac{2aq}{\sqrt{(q^2 - p^2)^2 + (2qa)^2}} = \frac{2a}{q\sqrt{\left[1 - \left(\frac{n^2}{n_1}\right)^2\right]^2 + \left[\frac{2a}{q}\right]^2}} \qquad (110)$$

It is most convenient to plot the ratio $\frac{I}{I_r} = y$ as ordinates to abscissæ representing $\frac{n_2}{n_1} = x$ (see Fig. 26).

A resonance curve so plotted enables us to determine the logarithmic decrement of the oscillation circuit with great ease. For if δ is the logarithmic decrement per semi-period of the circuit, then $2n_2\delta = \alpha$ and $2n_1\pi = q$. Hence—

$$\frac{2\alpha}{q} = \frac{2\delta}{\pi} \cdot \frac{n_2}{n_1}$$

Therefore
$$\frac{I}{I_r} = \frac{2\frac{\delta}{\pi} \cdot \frac{n_2}{n_1}}{\sqrt{\left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^2 + \left(\frac{2\delta}{\pi} \cdot \frac{n_2}{n_1}\right)^2}} \quad . \quad (111)$$



$\frac{n_2}{n_1}$ = Ratio of Frequencies.

Fig. 26.—A Resonance Curve.

or if $\frac{n_2}{n_1} = x$, then when x is near unity $1 + x$ is nearly 2, and we can transform (111) into—

$$\frac{I}{I_r} = \frac{1}{\sqrt{1 + \frac{(1-x)^2}{\left(\frac{\delta}{\pi}\right)^2}}} \quad . \quad . \quad . \quad . \quad . \quad (112)$$

$$\text{or} \quad \delta = \pi(1-x)\sqrt{\frac{I^2}{I_r^2 - I^2}} \quad . \quad . \quad . \quad . \quad (113)$$

The practical use of this last expression for the decrement is considerable. Owing to the difficulty of measuring spark resistance, and the fact that the high frequency resistance of a circuit can only be predetermined in a few cases, we are seldom able to obtain the resistance decrement of a circuit by direct calculation.

We can, however, proceed experimentally as follows: Insert in the secondary circuit a hot-wire ammeter so as to measure the value of the root-mean-square current. Since for the same circuit this R.M.S. value J is directly proportional to the maximum value I of the currents during each train, it follows that—

$$\frac{J^2}{J_r^2 - J^2} = \frac{I^2}{I_r^2 - I^2} \quad . \quad . \quad . \quad . \quad . \quad (114)$$

where the suffix r indicates the value of the current at its maximum, due to exact resonance.

If, then, we can measure or calculate from the capacity and inductance in the primary and secondary circuits the frequencies n_1 and n_2 for the various values of the secondary current J, we can plot a resonance curve of J in terms of the ratio $\frac{n_2}{n_1}$ as follows:—

Set off on some horizontal line a distance, OX (see Fig. 27), to represent unity, and on this line mark off various values of the ratio $\frac{n_2}{n_1}$ as abscissæ. Corresponding to these, set up ordinates representing the values of J^2, and taking the maximum ordinate XY to have a value, unity, on some scale, we obtain a curve, AYB, the ordinates of which represent the ratio of the square of the secondary current,

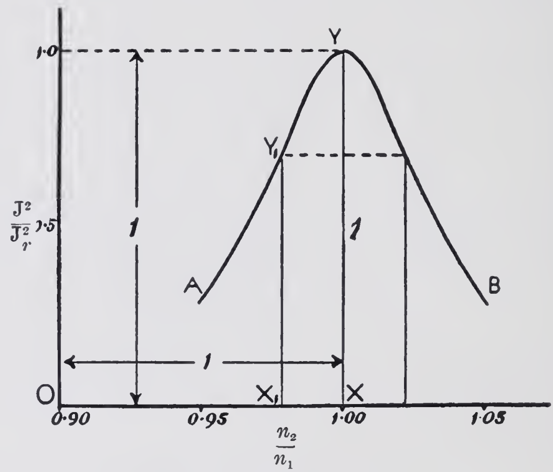


FIG. 27.—Determination of the Decrement of Electrical Oscillations by the aid of a Resonance Curve.

J^2, to square of the maximum current, J_r^2; and the corresponding abscissæ the ratio of the natural frequencies of the two circuits.

Then, if X_1Y_1 is some value of $\frac{J^2}{J_r^2}$ corresponding to a value of $\frac{n_2}{n_1}$ *not far from unity*, we have $XX_1 = 1 - \frac{n_2}{n_1}$ and

$$\frac{X_1Y_1}{\sqrt{(XY)^2 - (X_1Y_1)^2}} = \sqrt{\frac{J^2}{J_r^2 - J^2}}$$

Hence from (113) $\quad \delta = \pi(XX_1)\dfrac{X_1Y_1}{\sqrt{(XY)^2 - (X_1Y_1)^2}} \quad . \quad . \quad (115)$

The reader must, however, notice that this method of obtaining the decrement δ from the resonance curve is based on two assumptions—

(i.) The distance XX_1 must be small compared with OX, so that $1 - \frac{n_2}{n_1}$ is a small quantity compared with unity.

(ii.) The method is only valid when the decrement δ is small compared with π, so that $2n\delta = \alpha$ is small compared with $2n\pi = p$, as above assumed.

Hence the method only applies to the determination of the decrement of a feebly damped oscillatory circuit, or to one in which the decrement is not greater, say, than 0·1.

If the damping is not small, then we cannot neglect δ in comparison with π, and in plotting the resonance curve for potential and current we have to employ the complete equations (107) and (108). We then find that the resonance curves for potential and current plotted to the same ordinates $\frac{n_2}{n_1}$ are no longer identical or symmetrical, and moreover that the maximum ordinate of the curve does not coincide with abscissa $\frac{n_2}{n_1} = 1$. This leads to the conclusion that we

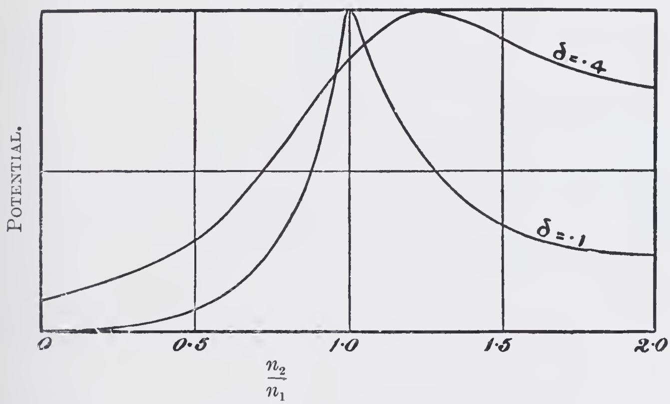


FIG. 28.—Resonance Curves plotted in Terms of Potential for Strongly Coupled Circuits.

have to distinguish between *isochronism* in two circuits and *resonance*, and that whilst these are identical for feebly damped circuits, they are not so for strongly damped circuits. The two diagrams in Figs. 28 and 29 for the resonance curves of potential and current for two circuits having decrements per half-period respectively of 0·1 and 0·4, show this distinction. These diagrams are taken, by kind permission, from the treatise by Professor J. Zenneck on "Electrical Oscillations and Wireless Telegraphy," p. 573.

14. Resonance between Two Coupled Circuits both having Damping.—The case of two inductively coupled oscillation circuits both having damping presents somewhat greater analytical difficulties in its discussion. It has been handled with ability by several writers. We shall first follow in outline the method employed by V. Bjerknes in dealing with this problem.[35] We assume that there are two circuits, both having capacity, inductance, and resistance, which are inductively connected. Let us suppose that oscillations are

[35] See V. Bjerknes, *Wied. Ann.*, 1895, vol. 55, p. 121; also *Ibid.*, 1891, vol. 44, p. 74.

excited in one circuit by means of a spark-gap as usual, and that these set up other oscillations in the adjacent secondary circuit. The problem is to predetermine the secondary current and the decrements and their relation to the constants of the two circuits. Let suffixes 1 and 2 refer to the primary and secondary circuits, let C, L, and R denote the capacity, inductance, and resistance of the circuits, α the damping factor, and δ the decrement, and p 2π times the frequency n. We have first to construct the differential equation expressing the instantaneous terminal potential difference of the condenser in the secondary circuit. Let v_2 be this potential at any time t. Then, as in the previous section, we have as the equation of potential difference between the terminals of the secondary circuit condenser the expression—

$$\frac{d^2v_2}{dt^2} + \frac{R_2}{L_2}\cdot\frac{dv_2}{dt} + \frac{1}{C_2L_2}v = \frac{E}{C_2L_2}\epsilon^{-\alpha_1 t}\cos p_1 t \quad . \quad . \quad (116)$$

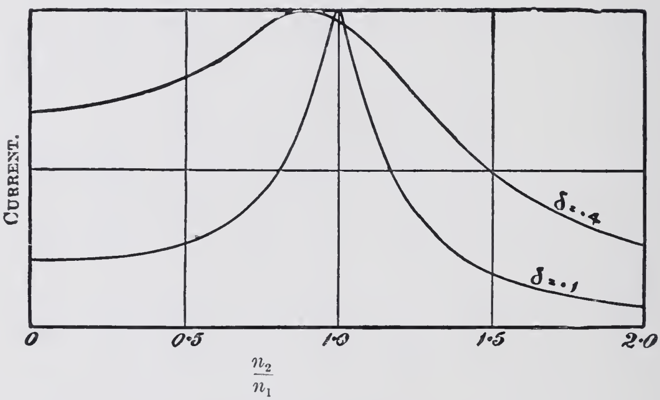


FIG. 29.—Resonance Curves plotted in Terms of Current for Strongly Coupled Circuits.

We assume, for the sake of avoiding purely analytical difficulties, that the impressed electromotive force in the secondary circuit has its maximum value E when $t = 0$, and that at this instant the oscillations in the secondary circuit begin so that $v_2 = 0$, and $\frac{dv_2}{dt} = 0$ when $t = 0$. Writing $2\alpha_2$ for $\frac{R_2}{L_2}$, and $p_2^2 + \alpha_2^2$ for $\frac{1}{C_2L_2}$ as before, we have, as the expression for the potential difference of the terminals of the condenser in the secondary circuit, the equation—

$$\frac{dv_2^2}{dt^2} + 2\alpha_2\frac{dv_2}{dt} + (p_2^2 + \alpha_2^2)v = \frac{E}{L_2C_2}\epsilon^{-\alpha_1 t}\cos p_1 t \quad . \quad (117)$$

The above expression indicates that the motion of electricity in the secondary circuit is due to a damped inducing oscillation in the primary circuit with period $\frac{2\pi}{p_1}$ and damping factor α_1.

To solve (117), differentiate all through twice with respect to time;

multiply the original (117) by $(p_1^2 - \alpha_1^2)$, the first differential by $2\alpha_1$; and add the results to the second differential equation. This eliminates the term $\epsilon^{-\alpha_1 t}\cos p_1 t$, and gives us a differential equation of the 4th order, viz.—

$$\frac{d^4v_2}{dt^4}+2(\alpha_1+\alpha_2)\frac{d^3v_2}{dt^3}+[(p_1^2+\alpha_1^2)+(p_2^2+\alpha_2^2)+4\alpha_1\alpha_2]\frac{d^2v_2}{dt^2}+[2\alpha_2(p_1^2+\alpha_1^2)$$
$$+2\alpha_1(p_2^2+\alpha_2^2)]\frac{dv}{dt}+[(p_2^2+\alpha_2^2)(p_1^2+\alpha_1^2)]v=0 \quad . \quad . \quad . \quad (118)$$

Replacing the differential coefficients by m^4, m^3, m^2, and m respectively, we have as the auxiliary equation a biquadratic in m.

The solution of (117) is found by taking the roots of the anxiliary biquadratic having the same coefficients term for term. These roots are easily seen to be—

$$-\alpha_1 \pm \sqrt{-1}p_1 \text{ and } -\alpha_2 \pm \sqrt{-1}p_2$$

Hence the solution of (117) is in the form—

$$v = V_1\epsilon^{-\alpha_1 t}\sin(p_1t+\theta_1) + V_2\epsilon^{-\alpha_2 t}\sin(p_2t+\theta_2) \quad . \quad (119)$$

This indicates that there are *two superimposed oscillations created in the secondary circuit.*

(i.) A *forced oscillation* of maximum amplitude V_1, having the same frequency and damping as the primary current.

(ii.) A *free oscillation* of maximum amplitude V_2, having the natural frequency and damping of the secondary circuit.

To find the values of the amplitudes V_1 and V_2, and the phase angles θ_1 and θ_2, we proceed as follows:—

Differentiate the solution (119) for v, and substitute the values of v and $\frac{dv}{dt}$ found from (119) in the original equation (117). We obtain the expression—

$$\frac{E}{L_2C_2}\epsilon^{-\alpha_1 t}\cos p_1t = V_1[p_2^2 - p_1^2 + (\alpha_2-\alpha_1)^2]\epsilon^{-\alpha_1 t}\sin(p_1t+\theta_1)$$
$$+ V_1[2p_1(\alpha_2-\alpha_1)]\epsilon^{-\alpha_1 t}\cos(p_1t+\theta_1) \quad . \quad (120)$$

Bearing in mind that $\frac{1}{L_2C_2} = p_2^2 + \alpha_2^2$, and that $\sqrt{A^2+B^2}\cos pt = A\cos(pt+\theta) + B\sin(pt+\theta)$, provided that $\tan\theta = \frac{B}{A}$, it follows at once that—

$$V_1 = \frac{p_2^2+\alpha_2^2}{\sqrt{[p_2^2-p_1^2+(\alpha_2-\alpha_1)^2]^2+4p_1^2(\alpha_2-\alpha_1)^2}}.E \quad (121)$$

$$\text{and } \tan\theta_1 = \frac{p_2^2-p_1^2+(\alpha_2-\alpha_1)^2}{2p_1(\alpha_2-\alpha_1)}$$

The above expressions give us the maximum amplitude and phase of the *forced* oscillation in the secondary circuit.

To find the same constant for the free oscillation, we must take

equation (119), and put $t = 0$ and $v = 0$; and also differentiate (119), and put $t = 0$ and $\frac{dv}{dt} = 0$. We then have—

$$\mathrm{V}_1 \sin \theta_1 + \mathrm{V}_2 \sin \theta_2 = 0$$

$$-\mathrm{V}_1 a_1 \sin \theta_1 + \mathrm{V}_1 p_1 \cos \theta_1 - \mathrm{V}_2 a_2 \sin \theta_2 + \mathrm{V}_2 p_2 \cos \theta_2 = 0$$

$$\left.\begin{array}{ll} \text{or} & \mathrm{V}_2 p_2 \sin \theta_2 = -\mathrm{V}_1 p_2 \sin \theta_1 \\ \text{and} & \mathrm{V}_2 p_2 \cos \theta_2 = -\mathrm{V}_1[(a_2 - a_1) \sin \theta_1 + p_1 \cos \theta_1] \end{array}\right\} . \quad (122)$$

Squaring and adding, we obtain—

$$\mathrm{V}_2^2 p_2^2 = (a_2 - a_1)^2 \mathrm{V}_1^2 \sin^2 \theta_1 + p_2^2 \mathrm{V}_1^2 \sin^2 \theta_1 + p_1^2 \mathrm{V}_1^2 \cos^2 \theta_1$$
$$+ 2p_1 \overline{a_2 - a_1} \mathrm{V}_1^2 \sin \theta_1 \cos \theta_1 \; . \; . \; . \; . \; . \; . \; . \quad (123)$$

and having regard to the value of $\tan \theta_1$ given in (121), we find that (123) reduces to—

$$\mathrm{V}_2^2 p_2^2 = \mathrm{V}_1^2[p_2^2 + (a_2 - a_1)^2] \; . \; . \; . \; . \quad (124)$$

Hence it follows that—

$$\frac{\mathrm{V}_2}{\mathrm{V}_1} = \frac{\sqrt{p_2^2 + (a_2 - a_1)^2}}{p_2}$$

and that
$$\mathrm{V}_2 = \frac{(p_2^2 + a_2^2)\sqrt{p_2^2 + (a_2 - a_1)^2}}{p_2\sqrt{[p_2^2 - p_1^2 + (a_2 - a_1)^2]^2 + 4p_1^2(a_2 - a_1)^2}} . \mathrm{E} \quad (125)$$

and
$$\tan \theta_2 = \frac{p_2}{a_2 - a_1} \cdot \frac{p_2^2 - p_1^2 + (a_2 - a_1)^2}{p_2^2 + p_1^2 + (a_2 - a_2)^2} \; . \; . \; . \; . \; . \; . \; . \quad (126)$$

The above expressions enable us to define the secondary current precisely.

Each potential oscillation, forced and free, acts to produce its own current in the secondary circuit, and if we call I_1 and I_2 the maximum values of the forced and free secondary currents, we have these related to the potential maxima as follows:—

$$I_1 = \mathrm{C}_2 \mathrm{V}_1 p_1$$
$$I_2 = \mathrm{C}_2 \mathrm{V}_2 p_2$$

Accordingly, we have the following expressions for the amplitude of the currents:—

$$\left.\begin{array}{l}\text{Forced current} \\ \quad\text{maximum} \\ \quad\text{amplitude}\end{array}\right\} = I_1 = \frac{p_1 \mathrm{E}}{\mathrm{L}_2\sqrt{[p_2^2 - p_1^2 + (a_2 - a_1)^2]^2 + 4p_1^2(a_2 - a_1)^2}} \quad (127)$$

$$\left.\begin{array}{l}\text{Free current} \\ \quad\text{maximum} \\ \quad\text{amplitude}\end{array}\right\} = I_2 = \frac{\sqrt{p_2^2 + (a_2 - a_1)^2} \, . \, \mathrm{E}}{\mathrm{L}_2\sqrt{[p_2^2 - p_1^2 + (a_2 - a_1)^2]^2 + 4p_1^2(a_2 - a_1)^2}} \quad (128)$$

Hence the actual current in the secondary circuit is the resultant of two damped oscillations, differing in phase and frequency. The further discussion of the problem is facilitated by adopting a procedure due to V. Bjerknes.[36]

[36] See V. Bjerknes, "On Electrical Resonance," *Wied. Ann.*, 1895, vol. 55, p. 121.

He assumes that we may consider the secondary current as a single current of variable amplitude expressed as a function of the time, of the form—

$$i = C_2\left(\frac{p_1 + p_2}{2}\right)M \cos (mt + m') \quad . \quad . \quad . \quad (129)$$

where M is a function of the time and of the damping factors and other circuit constants.

$$\text{Let } m = \frac{p_1 + p_2}{2}, \quad n = \frac{p_1 - p_2}{2}, \quad \mu = \frac{a_1 + a_2}{2}, \quad \nu = \frac{a_1 - a_2}{2}.$$

Let the original differential equation for the potential difference of the terminals of the secondary condenser be —

$$\frac{d^2v}{dt^2} + 2a_2\frac{dv}{dt} + (p_2^2 + a_2^2)v = \frac{E}{L_2C_2}\epsilon^{-a_1t} \sin (p_1t + \phi) \quad (130)$$

Bjerknes shows that the solution of the above equation can be given in the form—

$$v = M \sin (mt + m')$$

where—

$$M^2 = \frac{E^2}{16L_2^2C_2^2m^2(n^2 + \nu^2)}\left(P_1 + 2\,.\,\frac{1 + \cos 2\phi}{m}P_2 + 2\,.\,\frac{\sin 2\phi}{m}P_3\right) (131)$$

$$\left.\begin{aligned} \text{and} \quad P_1 &= \epsilon^{-2\mu t}(\epsilon^{-2\nu t} + \epsilon^{2\nu t} - 2 \cos nt) \\ P_2 &= \epsilon^{-2\mu t}(n\epsilon^{2\nu t} - n \cos 2nt - \nu \sin 2nt) \\ P_3 &= \epsilon^{-2\mu t}(\nu\epsilon^{2\nu t} - \nu \cos 2nt + n \sin 2nt) \end{aligned}\right\} \quad (132)$$

Bjerknes then discusses various cases, and delineates curves showing the variation of M with time.

1st case. Let the primary and secondary circuits have the same periodic time and damping, viz. $p_1 = p_2$ and $a_1 = a_2$. Then we have—

$$M = \pm\frac{E}{2L_2C_2m}\,.\,t\,.\,\epsilon^{-\mu t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (133)$$

The graph of this equation is shown in Fig. 30 (A). In this case the amplitude of the oscillations first increases and then slowly falls away again.

2nd case. Let the two circuits have equal periodic times but unequal damping. Then—

$$M = \pm\frac{E}{4L_2C_2m\nu}\epsilon^{-\mu t}(\epsilon^{-\nu t} - \epsilon^{\nu t}) \quad . \quad . \quad . \quad (134)$$

The graph of this equation is given in Fig. 30 (B) for logarithmic decrements $\delta_1 = 0{\cdot}4$, $\delta_2 = 0{\cdot}04$.

3rd case. Let the damping of the two circuits be the same, but the frequencies different. Then we have—

$$M = \pm\frac{E}{2L_2C_2mn}\epsilon^{-\mu t} \sin nt \quad . \quad . \quad . \quad . \quad (135)$$

The graph of this equation is shown in Fig. 30 (D), and it presents

us with that periodic waxing and waning which is known in acoustics as the phenomenon of *beats*.

4th case. Let the damping and frequency of the two circuits be different, then the value of M is given in (131), and the graph will vary according to the relative values of the constants, but two cases are shown in Fig. 30 (E and F). Bjerknes then passes on to show how the *integral value* or *mean-square value* of the resultant secondary current can be calculated.

If we denote the mean-square value of the potential difference of the terminals of the secondary circuit condenser by U, and the corresponding value of the current by J, then U is defined by the equation—

$$U^2 = \int_0^\infty v^2 dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (136)$$

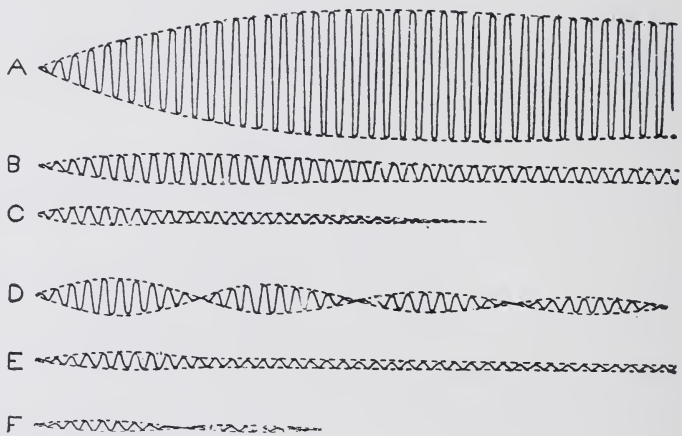


FIG. 30.—Bjerknes' Curves representing Various Types of Possible Secondary Oscillations.

since, owing to the frequency of the oscillations, a time of 1 second may be considered to be *infinite* as far as the decay of oscillations is concerned. Then, since $v = M \sin(mt + m')$—

$$v^2 = \frac{M^2}{2} - \frac{M^2}{2} \cos 2(mt + m') \quad . \quad . \quad . \quad . \quad (137)$$

In taking the integral, that part due to the cosine term of the above equation is zero, and hence—

$$U^2 = \tfrac{1}{2}\int_0^\infty M^2 dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (138)$$

Also the mean-square value of the current is given by—

$$J^2 = C_2^2 m^2 U^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (139)$$

where C_2 is the capacity of the secondary condenser. Hence—

$$J^2 = \tfrac{1}{2} C_2^2 m^2 \int_0^\infty M^2 dt \quad . \quad . \quad . \quad . \quad . \quad (140)$$

We must refer the reader to Bjerkne's paper (*loc. cit.*) for the steps of the reasoning by which he finally deduces an important equation for the mean-square value of the secondary current, which in our notation is—

$$J^2 = \frac{E^2}{16L_2^2} \cdot \frac{\alpha_1 + \alpha_2}{\alpha_1\alpha_2} \cdot \frac{1}{(p_1 - p_2)^2 + (\alpha_1 + \alpha_2)^2} \quad . \quad . \quad (141)$$

Since—

$$i = C_2 \frac{dv}{dt}$$

we have—

$$J^2 = \int_0^\infty i^2 dt = C_2^2 \int_0^\infty \left(\frac{dv}{dt}\right)^2 dt$$

If we substitute the values of V_1 and V_2 given in (120) and (125) in the equation (119), and then differentiate with regard to t, square and integrate with regard to t, and neglect powers of $(p_1 - p_2)$ and $(\alpha_1 - \alpha_2)$, we reach, after some troublesome reductions, the above equation. (See also "La Télégraphie sans fil," by MM. J. Boulanger and G. Ferrié, 7th ed., p. 165.)

This equation gives us the value of the current which would be read on a hot-wire ammeter of suitable type inserted in the secondary current.

It shows us that J increases as p_1 and p_2 or the frequencies of the two circuits become more nearly equal. Let us denote by J_r the value of the secondary current when $p_1 = p_2$, and call J_r the *resonance current;* then—

$$J_r^2 = \frac{E^2}{16L_2^2} \cdot \frac{1}{\alpha_1\alpha_2(\alpha_1 + \alpha_2)} \quad . \quad . \quad . \quad . \quad . \quad (142)$$

Accordingly, the ratio of J^2 to J_r^2 is given by—

$$\frac{J^2}{J_r^2} = \frac{(\alpha_1 + \alpha_2)^2}{(p_1 - p_2)^2 + (\alpha_1 + \alpha_2)^2} \quad . \quad . \quad . \quad . \quad (143)$$

$$\text{Hence} \quad \frac{J_r^2 - J^2}{J^2} = \frac{(p_1 - p_2)^2}{(\alpha_1 + \alpha_2)^2}$$

$$\text{or} \quad (\alpha_1 + \alpha_2) = (p_1 + p_2)\frac{J}{\sqrt{J_r^2 - J^2}} \quad . \quad . \quad . \quad . \quad (144)$$

If δ_1 and δ_2 are the logarithmic decrements per semiperiod of the two circuits, then $\alpha_1 = 2n_1\delta_1$, and $\alpha_2 = 2n_2\delta_2$. Hence if we insert these values of α_1 and α_2 in (144), and assume that *the frequencies of the two circuits n_1 and n_2 are nearly the same*, we can write (144) in the form—

$$\delta_1 + \delta_2 = \pi\left(1 - \frac{n_2}{n_1}\right)\frac{J}{\sqrt{J_r^2 - J^2}} \quad . \quad . \quad . \quad . \quad (145)$$

This useful equation gives us the means of determining the sum of the decrements of the two circuits when we have a resonance curve plotted showing the variation of $\frac{J}{J_r^2}$ with $\frac{n_2}{n_1}$. Thus, suppose we insert a suitable hot-wire ammeter in the secondary circuit and vary the

inductance of that circuit so as to change its natural time period n_2, and if we know n_1 we can plot a curve, as in Fig. 27, called a resonance curve, in which the ordinates represent the values of $\frac{J^2}{J_r^2}$ and the abscissæ denote the fraction $\frac{n_2}{n}$. This curve has a maximum ordinate equal to unity, and a corresponding abscissa also equal to unity. Draw any other ordinate *near to* the maximum and let x denote $1 - \frac{n_2}{n_1}$ and y denote $\frac{J^2}{J_r^2}$. Then from (145) we have—

$$\delta_1 + \delta_2 = \pi x \sqrt{\frac{y}{1 - y}} \quad . \quad . \quad . \quad . \quad . \quad (146)$$

and the measurement of x and y enables us to find $\delta_1 + \delta_2$. If, then, we can calculate one decrement from other data, we have the second decrement from this last equation.

This is the equation which was applied to determine the decrement of an oscillatory circuit having a spark gap in it in the researches of P. Drude, to which reference has been already made in § 5.

It is sometimes convenient to employ equation (146) in the form—

$$y = \frac{J^2}{J_r^2} = \frac{1}{1 + \dfrac{\pi^2 x^2}{(\delta_1 + \delta_2)^2}}$$

This equation holds good only when $x = 1 - \frac{n_2}{n_1}$ is small, and when δ_1 and δ_2 are also small compared with π.

In the Paper by Bjerknes, above mentioned (*Wied. Ann.*, vol. 55, 1895, p. 145), he proceeds to show how we can transform the equation (143) for the ratio of the mean-square values of the secondary current J^2 to the resonance current J_r^2 into another form. Let ω stand for the sum of the decrements $\delta_1 + \delta_2$ per semiperiod, or for the mean value of the decrements of the primary and secondary circuits, and let T_1 be the time period of the oscillator or primary circuit, and T_2 that of the secondary circuit or resonator, then Bjerknes proves that—

$$\frac{J^2}{J_r^2} = \frac{\omega^2 T_2^2 + \pi^2 S(T_1 - T_2)}{\omega^2 T_2^2 + \pi^2 (T_1 - T_2)^2}$$

where S is a certain parameter, the meaning of which will appear presently.

If we put y for J^2, Y for J_r^2, X for T_2, and x for T_1, the equation (141) transforms into—

$$\frac{y}{Y} = \frac{\omega^2 X^2 + \pi^2 S(x - X)}{\omega^2 X^2 + \pi^2 (x - X)^2} \quad . \quad . \quad . \quad . \quad . \quad (147)$$

The above equation is the equation of the resonance curve. It can easily be thrown into the form—

$$x^2 y - Axy - Bx + Cy + D = 0 \quad . \quad . \quad . \quad (148)$$

which is the expression for a curve of the third degree.

If the expression (147) is rearranged in terms of $(x - X)$ and $(y - Y)$, it can be put into the form—

$$\pi^2 y(x - X)^2 - \pi^2 SY(x - X) + \omega^2 X^2(y - Y) = 0 . \quad (149)$$

The point $x = X$ and $y = Y$ is then a point on the curve. Bjerknes calls this the *point of isochronism* It is a point near to the maximum value, but not coincident with it.

If we put $y = Y$ in (147), it gives us $(x - X) = S$, which shows that S represents the length of a chord through the point of isochronism.

If the curve represented by (147) or (148) is delineated (see Fig. 31), and if we draw a chord across it parallel to the axis of x, and call x_1 and x_2 the abscissæ of these intersections, we have $(x_1 - X)$ and $(x_2 - X)$ as roots of the equation (149), and therefore by the theory of equations we have—

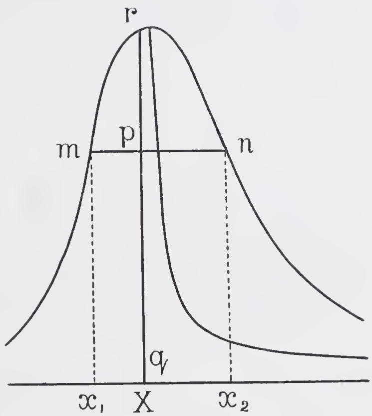


FIG. 31.

$$(x_1 - X) + (x_2 - X) = S\frac{Y}{y}$$

$$(x_1 - X)(x_2 - X) = \frac{\omega^2 X^2(y - Y)}{\pi^2 y}$$

The quantity—

$$\tfrac{1}{2}[(x_1 - X) + (x_2 - X)]$$

or $\frac{x_1 + x_2}{z} - X$ represents the distance between the middle point of this chord and the ordinate of the point of isochronism. If we call this distance z, then we have—

$$yz = \frac{SY}{2} = \text{a constant} \quad . \quad . \quad . \quad . \quad . \quad (150)$$

This shows that *the locus of the middle points of all the chords of the resonance curve drawn parallel to the axis of* x is an *equilateral hyperbola.*

The asymptotes of this hyperbola are the axis of x and the ordinate of the point of isochronism.

If, then, we draw the resonance curve and bisect all the chords, we can describe the hyperbola and find its asymptote, and hence the point $x = X$, $y = Y$.

If we draw any chord mn near the top (see Fig. 31), it cuts this asymptote, and is cut by it into two sections, and these four lengths are—

$$\left.\begin{aligned} mp &= x_1 - X = a \\ np &= x_2 - X = b \\ qp &= \quad y \quad = c \\ rp &= Y - y = d \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (151)$$

If we then insert the values of $x_1 - X$, $x_2 - X$, y and $Y - y$ given in (151) in equation (149), we arrive at the equation—

$$\omega^2 = \frac{abc}{d}\frac{\pi^2}{X^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (152)$$

$$\text{or} \quad \omega = \frac{\pi}{X}\sqrt{\frac{abc}{d}} = \delta_1 + \delta_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (153)$$

Hence the sum of the decrements of the oscillator and resonator, or of the two coupled circuits, can be obtained from the resonance curve by drawing the equilateral hypolata, which is the locus of the middle points of all its chords, and finding its vertical asymptote.

We shall apply this theorem, in a later chapter, to the determination of the numerical values of the decrement in certain cases.

A very masterly discussion of the problem of the inductive transformation of electric oscillations has also been given by Professor P. Drude in a well-known memoir.[37] He discusses the theory of an oscillation transformer or Tesla coil, consisting of a secondary circuit wound on a cylinder of length h and diameter d, in one or more layers of wire, and embraced by a primary circuit of one or a few turns of wire, the primary circuit being a circle having its centre on the axes of the secondary circuit.

He takes L_{11} to denote the self-inductance of the primary, and L_2^2 that of the secondary, and L_{12} to denote the mutual inductance of the secondary on the primary, and L_{21} that of the primary circuit on the secondary. In the case of two simple linear circuits with currents equal in all parts of the circuit, we should have $L_{12} = L_{21} = M$, or the mutual inductance of the two circuits. In the case of such an oscillation transformer as is here discussed, L_{21} is always greater than L_{12} in the ratio—

$$L_{21} : L_{12} = 1 : \sin \pi\frac{a}{h}$$

where a is some quantity less than the length h of the secondary spool.

The reason for this difference is that the total flux of induction produced by the actual current of unit strength in the centre coil of the secondary circuit is less than that which would be produced by a current having the same value, viz. unit strength in all parts of the secondary coil, because the actual current in the secondary coil is greatest in the centre of the wire and zero at the terminals or open ends. Drude then defines the coefficient of coupling k by the expression—

$$k^2 = \frac{L_{12} \cdot L_{21}}{L_{11} \cdot L_{22}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (154)$$

[37] P. Drude, "Über induktiv Erregung zweier Elektrische Schwingungskreise mit Anwendung auf Perioden und Dampfungsmessung Tesla transformatoren und Drahtlose Telegraphie," *Ann. der Physik*, 1904, vol. 13, p. 512.

If, then, v_1 is the potential difference of the primary condenser terminals at any instant, and v_2 that of the secondary terminals at the same instant, Drude establishes two equations which in our notation are as follows:—

$$L_{11}C_1\frac{d^2v_1}{dt^2} - L_{12}C_2\frac{d^2v_2}{dt^2} + R_1C_1\frac{dv_1}{dt} + v_1 = 0 \quad . \quad . \quad (155)$$

$$L_{22}C_2\frac{d^2v_2}{dt^2} - L_{21}C_1\frac{d^2v_1}{dt} + R_2C_2\frac{dv_2}{dt} + v_2 = 0 \quad . \quad . \quad (156)$$

and obtains solutions for these in the form—

$$v_1 = A\epsilon^{x_1t} + A_2\epsilon^{x_2t} + A_3\epsilon^{x_3t} + A_4\epsilon^{x_4t} \quad . \quad . \quad . \quad (157)$$

$$v_2 = B\epsilon^{x_1t} + B_2\epsilon^{x_2t} + B_3\epsilon^{x_3t} + B_4\epsilon^{x_4t} \quad . \quad . \quad (158)$$

and finally, by a long course of reasoning, he proves that if the circuits are adjusted to resonance, so that $L_{11}C_1 = L_{22}C_2$, we have the value of the secondary terminal potential difference given by the expression—

$$v_2 = \frac{\rho}{2}V_1\sqrt{\frac{C_1}{C_2}\cdot\frac{L_{21}}{L_{12}}\cdot\frac{k^2}{k^2 - \left(\frac{\delta_1 - \delta_2}{\pi}\right)^2}} \quad . \quad . \quad . \quad (159)$$

where V_1 is the maximum value of the primary condenser potential difference, and ρ is a function of the sum $(\delta_1 + \delta_2)$ of the two logarithmic decrements per semi-period, δ_1 and δ_2 of the primary and secondary circuits when separate, and also of the coefficient of coupling, k. The function expressing ρ is of the form—

$$\rho = \epsilon^{At}\cos Pt - \epsilon^{Bt}\cos Qt \quad . \quad . \quad . \quad . \quad (160)$$

where A, B, P, and Q are functions of $\delta_1 + \delta_2$, k and the frequencies of the two circuits. Hence v_2 has its maximum value corresponding to the maximum value of ρ. Drude gives a series of curves, reproduced in Fig. 32, which delineate the form of the function expressing ρ in terms of k for certain values of $\delta_1 + \delta_2$ between 0·15 and 1·00. It is seen that these curves all have a maximum ordinate corresponding to a coefficient of coupling k near to 0·6, and also that for the value $k = 1$ the value of ρ is for all curves 0·5. If δ_1 and δ_2 are both zero, then ρ has the value unity for all values of k. Hence, if we denote the maximum value of ρ by $\bar{\rho}$ for any value of $\delta_1 + \delta_2$, we can express the maximum value of the secondary terminal potential difference V_2 by the equation—

$$V_2 = \frac{\bar{\rho}}{2}V_1\sqrt{\frac{C_1}{C_2}\cdot\frac{L_{21}}{L_{12}}\cdot\frac{k^2}{k^2 - \left(\frac{\delta_1 + \delta_2}{\pi}\right)^2}} \quad . \quad . \quad . \quad (161)$$

If, then, $\delta_1 + \delta_2 = 0$, we have $\bar{\rho} = 1$ and—

$$V_2 = \frac{V_1}{2}\sqrt{\frac{C_1}{C_2}}\cdot\sqrt{\frac{L_{21}}{L_{12}}} \quad . \quad . \quad . \quad . \quad . \quad (162)$$

This expression for the ratio of $\frac{V}{V_1}$ for the undamped oscillations becomes identical with that given by Oberbeck if $L_{21} = L_{12}$. From the curves given in Fig. 32 we can calculate the ratio of the maximum secondary terminal potential difference V_2 to the primary condenser terminal potential difference for any assumed value of k and for values $\delta_1 + \delta_2$ corresponding to the curves given.

Thus, suppose the decrements of the circuits are such that $\delta_1 + \delta_2 = 0{\cdot}15$, and that the coupling is such that $k = 0{\cdot}6$. We see then

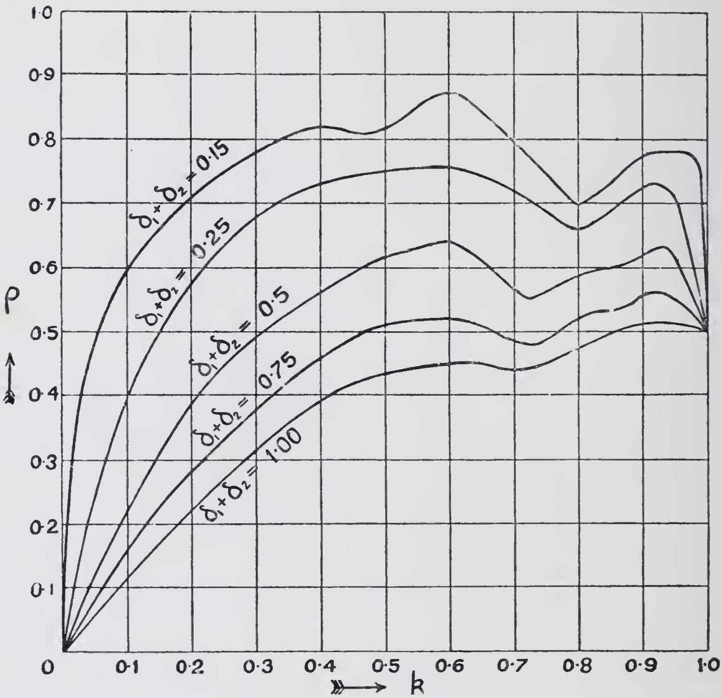


FIG. 32.—Drude's Curves.

from the curves that $\rho = 0{\cdot}87$, and since $\left(\frac{\delta_1 + \delta_2}{\pi}\right)^2 = \frac{1}{441}$, we can say that the secondary terminal potential difference is 87 per cent. of that which it would be if the circuits were undamped, and the same primary charging voltage employed.

In the course of his analysis Drude establishes an equation for the mean-square value of the secondary current J^2, which, when expressed in our notation, is as follows :—

$$J^2 = \frac{V_1^2}{16} \cdot \frac{L_{21}^2}{L_{11}^2 \cdot L_{22}^2} \cdot \frac{a_1 + a_2}{a_1 a_2} \cdot \frac{1}{(p_1 - p_2)^2 + (a_1 + a_2)^2} \cdot \quad (163)$$

where a_1 and a_2 are the damping factors of the two circuits. This

equation had already been obtained by Bjerknes (see § 14 of this chapter). If we bear in mind that the maximum value of the current in the primary circuit $I_1 = \frac{V_1}{L_{11}p_1}$, and that the maximum value of the electromotive force created in the secondary circuit by the primary current is $L_{21}I_1p_1$, we see that $\frac{V_1L_{21}}{L_{11}}$ is the same quantity as that denoted by E in the expression of Bjerknes (see equation 142 of this chapter), and that the expressions therefore given for J^2 by Drude and Bjerknes agree with one another.

It follows, therefore, that the maximum value of the mean-square secondary current in an oscillation transformer is given by the expression—

$$J^2_{\max} = \frac{V_1^2}{16} \cdot \frac{L_{21}^2}{L_{11}^2 \cdot L_{22}^2} \cdot \frac{1}{\alpha_1\alpha_2(\alpha_1 + \alpha_2)} \quad . \quad . \quad . \quad (164)$$

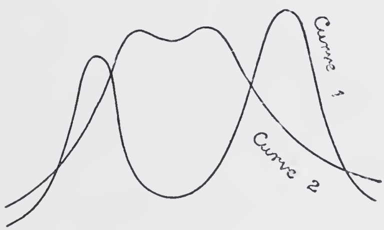


FIG. 33.—Double-humped Resonance Curves for Coupled Circuits.

or if we put for α_1 and α_2 their values in terms of the decrements and common frequency n, we have $\alpha_1 = 2n\delta_1$ and $\alpha_2 = 2n\delta_2$. Hence—

$$J^2_{\max} = \frac{V_1^2}{128} \cdot \frac{L_{21}^2}{L_{11}^2 \cdot L_{22}^2 \cdot n^3} \cdot \frac{1}{\delta_1\delta_2(\delta_1 + \delta_2)} \quad . \quad . \quad . \quad (165)$$

If the coupling is such that $L_{12} . L_{21} = L_{21}^2 = k^2L_{11}L_{22}$, we have, since $C_1L_{11} = C_2L_{22} = \frac{1}{4\pi^2n^2}$—

$$J^2_{\max} = V_1^2\frac{C_1C_2}{8} \cdot \frac{n\pi^4k^2}{\delta_1\delta_2(\delta_1 + \delta_2)} \quad . \quad . \quad . \quad . \quad (166)$$

The above formula is very convenient for calculation, and shows us, amongst other things, the importance of securing a small decrement for the primary or condenser circuit if the mean-square value of the secondary current is to be large. We shall find this formula of use to us in calculating the current in the antenna of a wireless telegraph transmitter plant.

If we take the resonance curve in the above manner for a pair of coupled circuits in resonance, then, as proved above, we shall have oscillations of two frequencies set up in each circuit, and therefore find two frequencies, corresponding to which there will be maximum currents in the tertiary or cymometer circuit. Hence the resonance curve, when described, will be found to be a curve with double hump,

as in Fig. 33. If these humps are fully separated, which implies that the frequencies of the two oscillations lie far apart, then we may apply the above-mentioned method of determining the decrement to each hump separately. This is the case when the coupling is very close.

If, however, the coupling is loose, then the humps are not widely separated, as in Curve 1, Fig. 33, but tend to run into one hump with a depression on its summit, as in Curve 2, Fig. 33. It is then impossible to apply the above method of determining the decrement to each hump separately. C. Fischer has, however, described a method, due to J. Zenneck, by which the two nearly superimposed waves can be examined separately.[38] If I. and II. in Fig. 34 represent the coupled oscillatory circuits and M the measuring circuit, then loops 1 and 2 are formed in the circuits I. and II., which are coupled inductively with two loops 3 and 4 placed in the measuring circuit. If loops 1 and 2 are placed so far apart that they do not sensibly act on each other, and if 4 is coupled with 2, then there will be two waves set up in the measuring circuit. If the measuring circuit is brought into a condition of resonance with one wave by altering its capacity, then on bringing the loop 3 near to loop 1 a minimum reading of the ammeter in the measuring circuit will be found, so that any approach or removal of 3 to or from 1 increases the current. If 3 is kept in this position the resonance curve obtained by continuously varying the capacity and inductance of M shows only one maximum, which is that due to the wave of one frequency. By reversing the connections of loop 1 and slightly shifting 3 the resonance curve of the other wave can be drawn. The principle which lies at the base of this method is that the oscillatory circuits I. and II. are each the seat of a current, which may be considered to be the sum of two damped oscillations differing in amplitude, damping, and frequency. Thus the solution of the differential equation (118) of the fourth order is of the form—

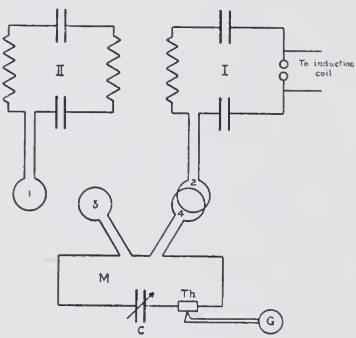


Fig. 34.

$$i_1 = A_1\epsilon^{-\delta t} \sin pt + B_1\epsilon^{-\gamma t} \sin qt \quad . \quad . \quad . \quad (167)$$

and for the secondary circuit we have—

$$i_2 = A_2\epsilon^{-\delta t} \sin pt + B_2\epsilon^{-\gamma t} \sin qt \quad . \quad . \quad . \quad (168)$$

and hence for the resultant magnetic field in the neighbourhood of these circuits we have—

$$M = (a_1A_1 + a_2A_2)\epsilon^{-\delta t} \sin pt + (a_1B_1 + a_2B_2)\epsilon^{-\gamma t} \sin qt \quad (169)$$

where a_1 and a_2 are some constants depending on the locality.

[38] See C. Fischer, "A Method of examining separately the Two Waves on Coupled Oscillators," *Ann. der Physik*, vol. 19, p. 182, 1906, or *Science Abstracts*, vol. ix. A, 1906, Abstract No. 573.

Hence if we couple the circuits I. and II. independently to the measuring circuit, but in different degrees, and bear in mind that the current in circuit I. is also exactly opposite in phase to that in II., we can partly neutralize the effect of one of the oscillations in II. in the measuring circuit by the action of the same oscillation in I., and thus leave the measuring circuit only influenced by one of the oscillations existing in the circuit II. C. Fischer gives in his paper

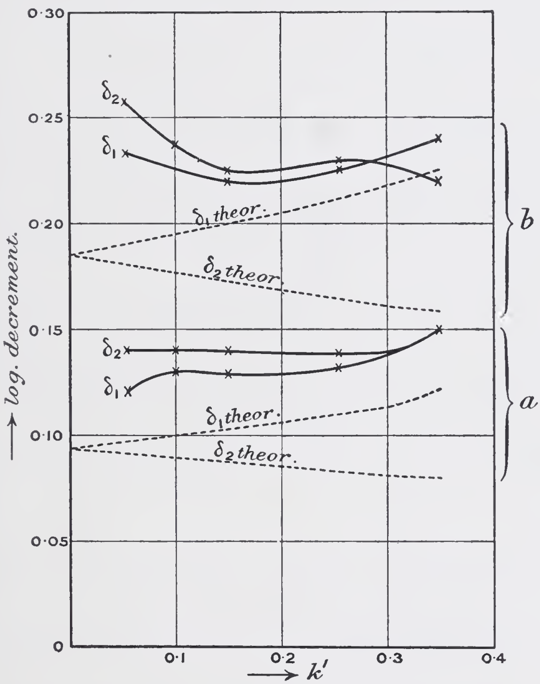


FIG. 35.—Curves representing the Results of C. Fischer's Comparisons of the Observed and Calculated Decrements for Coupled Circuits.

(*loc. cit.*) examples of very loosely, moderately loosely, and tightly coupled circuits, and delineates the resultant resonance curves, and determines by this means the decrements of the two oscillations. He gives the following values for certain oscillation circuits of the decrements of the two oscillations for loose, fairly loose, and tight coupling determined in this manner :—

Coupling.	Decrement δ.	Decrement γ.
Loose = 3%	0·08 (0·07)	0·09 (0·056)
Moderate = 7%	0·057 (0·063)	0·068 (0·075)
Tight = 39%	0·076 (0·08)	0·09 (0·09)

The values put in brackets denote the decrements which were obtained by applying the Bjerknes method directly to each hump as if it were a separate resonance curve. The differences show that for values of the coupling below, say, 10 per cent., the two methods give

different values. In the same manner there is a concordance between the values of the coefficient of coupling obtained from observations with the two humps if these are wide apart, but not if they are close together.

The theory of the damping of the two oscillations in coupled circuits has also been examined by C. Fischer,[39] and the results of experiments by the above method compared with the predictions of the theory given by P. Drude.[40] Fischer found that the frequencies of

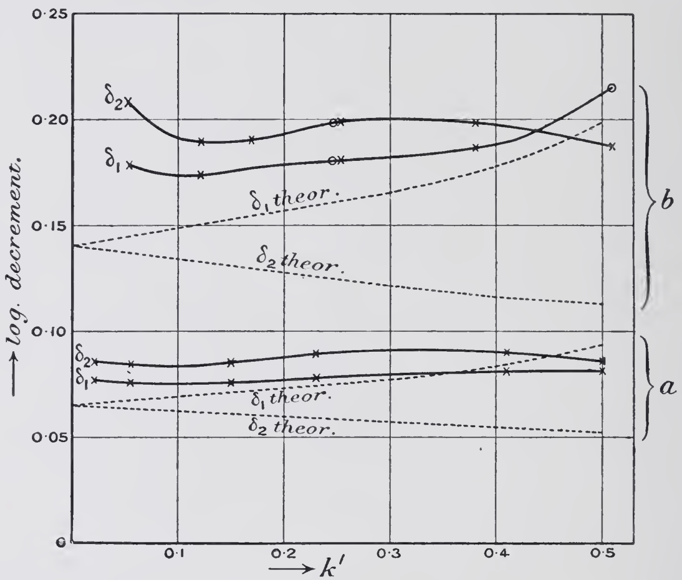


FIG. 36.—Curves representing the Results of C. Fischer's Comparisons of the Observed and Calculated Decrements in Coupled Circuits.

the two oscillations n_1 and n_2 existing in two coupled circuits, each of natural free frequency N, are given by the equations—

$$\frac{N^2}{n_1^2} = 1 - k, \qquad \frac{N^2}{n_2^2} = 1 + k \quad . \quad . \quad . \quad . \quad (170)$$

and hence that—

$$\frac{1}{n_1^2} + \frac{1}{n_2^2} = \frac{2}{N^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (171)$$

Fischer confirmed the above relation both for large and small damping coefficients. Experiment showed, however, that Drude's equations for the decrements δ_1 and δ_2 of these two oscillations, viz.—

$$\delta_1 = \frac{D_1 + D_2}{2}\frac{n_1}{N} \qquad \delta_2 = \frac{D_1 + D_2}{2}\frac{n_2}{N}$$

[39] See C. Fischer, "On Coupled Condenser Circuits," *Ann. der Physik*, vol. 22, p. 265, 1907, or *Science Abstracts*. vol. x. A, 1907, *abs.* 702.
[40] See P. Drude, *Ann. der Physik*, vol. 13, p. 528, 1904.

where D_1 and D_2 are the decrements of the oscillations in the two coupled circuits when separate, is not even true qualitatively, as the oscillation of greatest frequency has not *always* or even generally the largest decrement. Also the actual decrements found are larger than those predicted by the theory. This has also been noticed by M. Wien.[41]

The results of C. Fischer's observations on this matter are delineated in Figs. 35 and 36, where the dotted lines represent the decrements of a pair of coupled circuits calculated by the formulæ of Drude, and the firm lines the observed decrements for various couplings k'. These curves show the discrepancy between the observed and calculated decrements.

We shall return to the consideration of this subject in discussing the action of radiotelegraphic transmitters of the inductively coupled type in Chap. VIII., see § 10.

Some examples of the use of resonance curves in calculating the decrement of electric oscillations and making measurements of spark resistance will be found in Chap. VI., § 20.

[41] See M. Wien, "The Intensity of the Two Waves in Coupled Transmitters," *Science Abstracts*, vol. ix. A, 1906, *abs.* 2076.

PART II.—ELECTRIC WAVES

CHAPTER IV

STATIONARY ELECTRIC WAVES ON WIRES

1. The Propagation of Electric Potential along a Conductor of Infinite Length.—Let us consider the case of a conductor infinitely long, consisting of a wire embedded in an insulator. Let the resistance, inductance, and capacity per unit of length of this wire be denoted by R, L, and C. Let the conductance of the insulator per unit of length of the wire be denoted by K.

Then if a periodic electromotive force is applied to some point in this circuit a current will be created in it.

Let the point of application of the electromotive force be taken as origin, and measure any distance x from it along the circuit. Consider an element of the conductor whose length is $\delta x = (x + \delta x) - x$ situated at this distance x from the origin.

Also at the point whose abscissa is x let the current in the conductor be denoted by i and the potential by v.

At the distance $x + \delta x$ the current will be $i + \frac{di}{dx}\delta x$, and the potential $v + \frac{dv}{dx}\delta x$.

The resistance, inductance, capacity, and dielectric conductance of the length δx of the conductor are $\mathrm{R}\delta x$, $\mathrm{L}\delta x$, $\mathrm{C}\delta x$, $\mathrm{K}\delta x$, respectively.

Hence the equations connecting v and i are obviously—

$$\mathrm{L}\frac{di}{dt} + \mathrm{R}i = \frac{dv}{dx} \quad \ldots \ldots \quad (1)$$

$$\mathrm{C}\frac{dv}{dt} + \mathrm{K}v = \frac{di}{dx} \quad \ldots \ldots \quad (2)$$

If both i and v vary in a simple harmonic manner, and if I and V are the maximum values of the current and potential during the period, then whatever lines be taken to represent I and V, the maximum values of $\frac{di}{dt}$ and $\frac{dv}{dx}$ will be represented by lines equal to pI and $p\mathrm{V}$ respectively, drawn at right angles to I and V, where p, as usual, denotes $2\pi n$.

Hence, if we consider only maximum values of the periodic functions and represent the vectors denoting them by complex quantities,

we can write the equations (1) and (2) as vector equations, as follows:—

$$jpLI + RI = \frac{dV}{dx}$$

$$jpCV + KV = \frac{dI}{dx}$$

$$\text{or } \frac{dV}{dx} = (R + jpL)I \quad . \quad . \quad . \quad (3)$$

$$\frac{dI}{dx} = (K + jpC)V \quad . \quad . \quad . \quad (4)$$

Separating the variables in (3) and (4) by differentiation, we have—

$$\frac{d^2V}{dx^2} = (R + jpL)(K + jpC)V \quad . \quad . \quad . \quad . \quad (5)$$

$$\frac{d^2I}{dx^2} = (R + jpL)(K + jpC)I \quad . \quad . \quad . \quad (6)$$

or, writing P for $\sqrt{R + jpL} \,.\, \sqrt{K + jpC}$, we obtain—

$$\frac{d^2V}{dx^2} = P^2V \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$\frac{d^2I}{dx^2} = P^2I \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The solutions of the above equations (7) and (8) are—

$$V = a\epsilon^{+Px} + b\epsilon^{-Px} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$I = \frac{P}{R + jpL}(a\epsilon^{+Px} - b\epsilon^{-Px}) \quad . \quad . \quad . \quad . \quad (10)$$

where a and b are constants of integration.

The quantity P is a complex quantity, and can be represented in the typical form $\alpha + j\beta$.

$$\text{Hence} \quad \sqrt{R + jpL} \,.\, \sqrt{K + jpC} = \alpha + j\beta \quad . \quad . \quad . \quad . \quad (11)$$

$$\text{and therefore} \quad \alpha^2 + \beta^2 = \sqrt{R^2 + p^2L^2} \,.\, \sqrt{K^2 + p^2C^2} \quad . \quad . \quad (12)$$

$$\text{also} \quad \alpha^2 - \beta^2 = RK - p^2LC$$

Accordingly—

$$2\alpha^2 = \sqrt{(R^2 + p^2L^2)(K^2 + p^2C^2)} + (RK - p^2LC) \,. \quad (13)$$

$$2\beta^2 = \sqrt{(R^2 + p^2L^2)(K^2 + p^2C^2)} - (RK - p^2LC) \,. \quad (14)$$

The quantity α is called the *attenuation factor* of the cable, and β is

the *wave-length factor*. They can be calculated when we know the *primary constants*, R, L, C, K and n.

Next let us suppose the cable to be of infinite length in one direction, and that the impressed electromotive force is placed at the origin or accessible end. Let it be of simple harmonic form and maximum value E.

Then obviously there will be a gradual decrease in maximum potential along the cable, which must be zero at the infinitely distant end. If we reckon x in the direction in which the potential *decreases*, then we must change x into $-x$ in the general solutions (9) and (10) to make them fit this particular case, because in obtaining the original equations (1) and (2) we assumed that v and i *increased* with x.

Making this change, we then note that when $x = 0$, $\mathrm{V} = \mathrm{E}$, and when $x = \infty$, $\mathrm{V} = 0$. It follows, therefore, that $b = 0$ and $a = \mathrm{E}$. Hence the solutions (9) and (10) when applied to the above case become transformed into—

$$\mathrm{V} = \mathrm{E}\epsilon^{-\mathrm{P}x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$I = \mathrm{E}\epsilon^{-\mathrm{P}x}\frac{\sqrt{\mathrm{K}+jp\mathrm{C}}}{\sqrt{\mathrm{R}+jp\mathrm{L}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

These equations give us the vector values of the potential and current at any point in the cable at a distance x from the origin at which a simple periodic electromotive force of maximum value E is applied.

$$\text{Since } \mathrm{P} = \alpha + j\beta \text{ and } \epsilon^{-j\beta x} = \cos\beta x - j\sin\beta x \quad . \quad (17)$$

we can write (15) and (16) in the form—

$$\mathrm{V} = \mathrm{E}\epsilon^{-\alpha x}(\cos\beta x - j\sin\beta x) \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$I = \mathrm{E}\frac{\sqrt{\mathrm{K}+jp\mathrm{C}}}{\sqrt{\mathrm{R}+jp\mathrm{L}}}\epsilon^{-\alpha x}(\cos\beta x - j\sin\beta x) . \quad . \quad (19)$$

The reader should note that the above expressions are complex quantities, and represent V and I considered as vectors.

If we require the mere magnitude or size of V and I, that is, the numerical values of the maximum potential and current at the point x in the cable, we have to put these equations (18) and (19) into the form $\mathrm{A} + j\mathrm{B}$, and then find the value of the modulus $\sqrt{\mathrm{A}^2 + \mathrm{B}^2}$ which expresses the magnitude in a scalar sense.

The reader should also notice the physical signification of the equation (18). It denotes that the maximum value V of the potential at any point in the cable is less than the maximum value of the impressed electromotive force E in the ratio $1 : \epsilon^{-\alpha x}$, and also that V is shifted backwards in phase relatively to E by an angle βx.

The factor $\epsilon^{-\alpha x}$ is called the *attenuation factor*, and the factor $(\cos\beta x - j\sin\beta x)$ is the *phase factor* for the distance x.

When we know α and β we can always graphically delineate the attenuation and phase difference. Hence as we proceed along the

cable the maximum potential varies from point to point in accordance with the law of a damped oscillation. These facts may be presented graphically as follows :—

Take a line OX (see Fig. 1) to indicate the cable, and set up a perpendicular OE to represent in magnitude and direction the

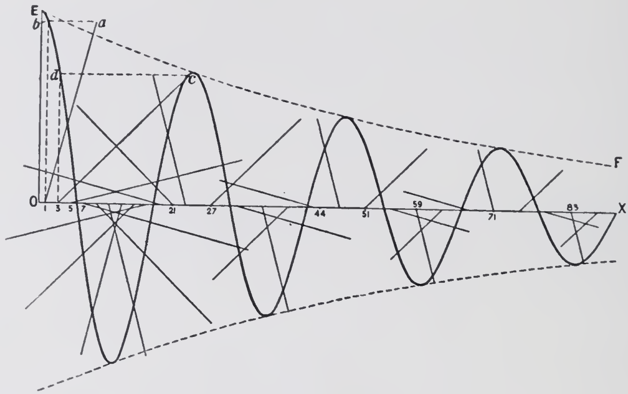
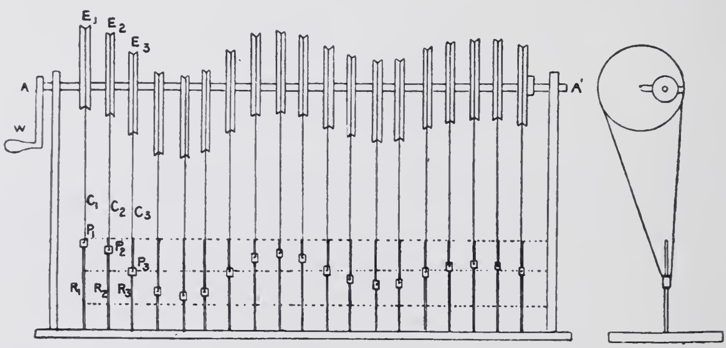


Fig. 1.—Delineation of a Curve representing the Variation of Maximum Potential along an Infinite Cable having a Simple Periodic Electromotive Force applied at one End, O.

maximum value of the electromotive force at the generator end. Then at equidistant points draw other lines decreasing in length in geometrical progression, and each shifted backwards or forwards in direction relatively to the preceding line by an equal angle. If we



Elevation. *Section.*

Fig. 2.—A Model illustrating the Propagation of an Alternating Current along a Cable of Infinite Length having a Simple Periodic Electromotive Force applied at one End.

suppose these lines to revolve with equal angular velocities round their ends as centres situated at equidistant intervals on the line OX ; then their projections at the same instant on vertical lines drawn through their centres will represent at that instant the actual voltage

at these points in the cable. The periodic change with time and distance may be represented by a working model made in the following manner: On a long steel axle, AA, are fastened a number of eccentric pulleys, E_1, E_2, E_3, etc. (see Fig. 2). The eccentricities of these wheels decrease in geometric progression, and each eccentric is set in phase backward behind its preceding neighbour by an equal angle. These wheels are embraced by endless cords, C_1, C_2, C_3, etc., of equal length attached to balls or blocks of metal, P_1, P_2, P_3, etc., sliding on vertical rods, R_1, R_2, R_3, etc., placed below each eccentric wheel.

When the axle carrying all the eccentrics is revolved by a handle, W, the blocks P_1, P_2, P_3, etc., will rise and fall with a nearly simple harmonic motion, and at any instant all the blocks will be situated on a sinuous curve of continually decreasing amplitude. As the eccentric axle revolves the motion of the balls will depict the progression of a wave of potential along a cable having capacity, inductance, resistance, and leakance.

The equations (18) and (19) contain within them the explanation of the limitations of telephony, but we are not here concerned to discuss them generally.

Since we are limiting our discussion to the effects of high frequency currents, we can reduce the complexity of the above expressions to a considerable degree. In cases where p is large the term pL in equations (13) and (14) is always much greater numerically than R, and likewise the numerical value of pC is greater than that of K. Accordingly, if we neglect R and K in comparison with pL and pC, the equations (13) and (14) for α and β reduce to—

$$2\alpha^2 = \mathrm{RK} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

$$2\beta^2 = 2p^2\mathrm{LC} - \mathrm{RK} \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$$\text{Therefore} \quad \beta^2 - \alpha^2 = p^2\mathrm{LC} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

In all cases likely to be met with in practice, RK is very small compared with p^2LC. Hence for high frequency oscillations it is sufficient to take—

$$\alpha = \sqrt{\tfrac{1}{2}\mathrm{RK}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

$$\beta = p\sqrt{\mathrm{LC}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Since $\cos(\beta x + 2\pi) = \cos \beta x$, it follows that $\cos \beta x = \cos \beta\left(x + \frac{2\pi}{\beta}\right)$ and therefore after moving along the conductor a distance $\frac{2\pi}{\beta}$ the current and potential again repeat themselves in value, or the wave length of both the current and potential curves is equal to $\frac{2\pi}{\beta}$. Hence, since in all cases of wave motion the wave velocity W is connected with the frequency n and the wave length λ by the equation—

$$\mathrm{W} = n\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

and since $\lambda = \dfrac{2\pi}{\beta}$ and $\beta = p\sqrt{CL}$, it follows that—

$$W = \frac{1}{\sqrt{CL}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

or the wave velocity is inversely as the oscillation constant of the cable per unit of length.

In those cases in which the insulation of the surrounding dielectric is so high that K = 0, and if pL is large compared with R, the vector equations (18) and (19) for the potential and current at any point in the wire at a distance x from the origin reduce to—

$$V = E\left(\cos\frac{2\pi}{\lambda}x - j\sin\frac{2\pi}{\lambda}x\right) \quad . \quad . \quad . \quad . \quad . \quad (27)$$

$$I = E\frac{\sqrt{C}}{\sqrt{L}}\left(\cos\frac{2\pi}{\lambda}x - j\sin\frac{2\pi}{\lambda}x\right) \quad . \quad . \quad . \quad (28)$$

We see, therefore, that in such a case the current in the wire at any point is determined solely by the capacity and inductance per unit of length of the wire, and, moreover, that on account of the shift of phase, the current is not even in the same direction at the same time at all points in the conductor.

At two places not very far apart electricity may be flowing in opposite directions at the same moment. Also, owing to the periodic character of the expressions, the same values of V and I repeat themselves cyclically as x continually increases.

The expressions (27) and (28) are vector expressions in the form $a + jb$. To obtain the numerical values for the potential and current at any point in the cable, we have to find the size of these vectors, viz. the value of $\sqrt{a^2 + b^2}$, and to obtain the actual potential at any moment we have to take the real part or horizontal step of the vector, viz. a.

Accordingly, the potential v at any distance along the cable x from the origin is given by the equation—

$$v = E\cos\frac{2\pi}{\lambda}x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

and similarly the current i by—

$$i = E\frac{\sqrt{C}}{\sqrt{L}}\cos\frac{2\pi}{\lambda}x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

As we proceed along the cable, therefore, the current and potential are distributed at any moment in accordance with the ordinates of a simple sine curve. These waves of potential and current move along the cable from the generating end with a speed equal to $\dfrac{1}{\sqrt{CL}}$.

2. Stationary Electric Waves on Wires of Finite Length.—We have next to consider the changes made in the above expressions

for the potential and current in the linear conductor when it is of finite length.

Consider first a wire infinitely extended in both directions. At two places separated by a distance $2l$ let two simple harmonic electromotive forces of opposite sign and of maximum value $+E$ and $-E$, that is, differing in phase by 180°, be applied. Then in the space between one of these sources and the point halfway between the two sources it is clear that the current must be distributed exactly as is the case in a finite wire of length l with one simple harmonic electromotive force of maximum value E placed at one end (see Fig. 3).

For it is clear that in a terminated or finite cable the current must always be zero at the end opposite to that at which the electromotive force is applied. Also in the case of the two opposite electromotive forces applied at a distance $2l$ in the infinite cable it is obvious that the current at the midpoint must always be zero. Again, we may cut away all that part of the infinite cable to the right or the left beyond the points of application of the electromotive forces without affecting the distribution of current in the length left behind. Hence in a piece of cable of finite length l having an electromotive force E

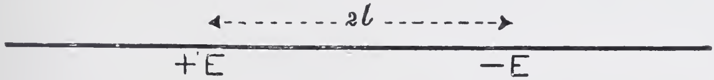


FIG. 3.—Two Sources of Alternating Electromotive Force in Opposite Phases placed in an Infinite Cable.

applied at one end the distribution of current must be the same, point for point, as it is in that part of an infinite cable which constitutes the half of the intercept between the points of application of the two opposite electromotive forces $+E$ and $-E$ separated by a distance $2l$.

We have seen that in an infinite cable the current I_1 at a distance x from the source E, is given by the equation—

$$I_1 = E\frac{\sqrt{K+jpC}}{\sqrt{R+jpL}}\epsilon^{-Px}$$

Hence, at a distance $2l - x$ from a source $-E$, the current I_2 must be—

$$I_2 = -E\frac{\sqrt{K+jpC}}{\sqrt{R+jpL}}\epsilon^{-P(2l-x)}$$

Now consider the infinite cable with the two sources $+E$ and $-E$ at a distance $2l$. At a point lying to the right of $+E$ and at a distance x the current I due to both sources must be the algebraic sum of those due to both separately, or must be expressed by—

$$I = E\frac{\sqrt{K+jpC}}{\sqrt{R+jpL}}\left\{\epsilon^{-Px} - \epsilon^{-P(2l-x)}\right\} \quad . \quad . \quad (31)$$

This, therefore, must be the expression for the current in a finite conductor of length l having an electromotive force E applied at one end, the equation (31) giving us the current at a point at a distance x from the source of electromotive force E.

To obtain the potential V we must refer to the equation (4), § 1, and note that I and V are connected by the relation—

$$\frac{dI}{dx} = (\mathrm{K} + jp\mathrm{C})\mathrm{V} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

Hence, differentiating (31) and recollecting that—

$$\mathrm{P} = \sqrt{\mathrm{K} + jp\mathrm{C}} \cdot \sqrt{\mathrm{R} + jp\mathrm{L}}$$

we have—

$$\mathrm{V} = \mathrm{E}\left\{\epsilon^{-\mathrm{P}x} + \epsilon^{-\mathrm{P}(2l-x)}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

In obtaining this last equation, we must note that since the x in (32) is measured in the direction in which the current and potential increase, we have to change x to $-x$ in (32) before employing it here; in other words, we must take the relation between V and I to be given by—

$$\mathrm{V} = -\frac{1}{\mathrm{K} + jp\mathrm{C}} \cdot \frac{dI}{dx} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

Therefore we see that the current in the finite cable of length l with harmonic electromotive force E applied at one end is obtained by taking the *difference* of two currents, one due to a source +E at the origin, and the other to an *electrical image* of this source (viz. +E) placed in imagination as much beyond the far end of the cable as the real source is from it.

Also the potential at any point is obtained by taking the *sum* of the potentials separately of the real source and an image of the source reflected in the far end of the cable.

If we consider that K may be neglected in comparison with pC, and also R in comparison with pL, as we may do, when dealing with electrical oscillations in ordinary wires, then we have the two following vector expressions for the potential V and current I at any distance x from one end of a finite wire of length l, a simple periodic electromotive force E being applied at the origin, viz.—

$$\mathrm{V} = \mathrm{E}\left\{\epsilon^{-\mathrm{P}x} + \epsilon^{-\mathrm{P}(2t-x)}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

$$I = \mathrm{E}\frac{\sqrt{\mathrm{C}}}{\sqrt{\mathrm{L}}}\left\{\epsilon^{-\mathrm{P}x} - \epsilon^{-\mathrm{P}(2l-x)}\right\} \quad . \quad . \quad . \quad . \quad . \quad (36)$$

But under the above conditions, when K and R are negligible compared respectively with pC and pL, we have seen that $\alpha = \sqrt{\frac{1}{2}\mathrm{RK}}$ and $\beta = p\sqrt{\mathrm{LC}}$. If K = 0, then $\alpha = 0$, and the attenuation is zero. This takes place when the conductivity of the dielectric is zero.

Under these conditions we have $P = j\beta = jp\sqrt{CL}$, and the equations (35) and (36) may be written in the form—

$$V = E\left\{\epsilon^{-j\beta x} + \epsilon^{-j\beta(2l-x)}\right\} \quad . \quad . \quad . \quad . \quad . \quad (37)$$

$$I = E\frac{\sqrt{C}}{\sqrt{L}}\left\{\epsilon^{-j\beta x} - \epsilon^{-j\beta(2l-x)}\right\} \quad . \quad . \quad . \quad (38)$$

or—

$$V = E\left[\left\{\cos \beta x + \cos \beta(2l - x)\right\} - j\left\{\sin \beta x + \sin \beta(2l + x)\right\}\right] \quad (39)$$

$$I = E\frac{\sqrt{C}}{\sqrt{L}}\left[\left\{\cos \beta x - \cos \beta(2l - x)\right\} - j\left\{\sin \beta x - \sin \beta(2l - x)\right\}\right] (40)$$

The above are vector expressions of the form $A + jB$. To obtain the scalar values or size, we must form the expressions equivalent to $\sqrt{A^2 + B^2}$, and we then have—

$$(V) = (E)\sqrt{2 + 2 \cos 2\beta(l - x)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (41)$$

$$(I) = (E)\frac{\sqrt{C}}{\sqrt{L}}\sqrt{2 - 2 \cos 2\beta(l - x)} \quad . \quad . \quad . \quad (42)$$

where (V), (E), and (I) stand for the scalar values of the vectors V, E, and I respectively.

In the above equations, if we put $x = l$, we have—

$$(V) = 2(E)$$
$$(I) = 0$$

which shows that at the free end of the wire the potential rises to twice the value at the generator end, whilst the current, of course, is zero.

Bearing in mind that under the conditions assumed $\beta = p\sqrt{CL}$, and also the velocity of propagation of the wave is $W = \frac{1}{\sqrt{CL}}$, and that $W = n\lambda$ where λ is the wave length, we have as a consequence $\beta = \frac{2\pi}{\lambda}$. Also let the length l of the conductor be some multiple of λ, so that $l = m\lambda$.

Then substituting these values in equations (41) and (42) and squaring, we have—

$$(V)^2 = (E)^2\left(2 - 2 \cos \frac{4\pi}{\lambda}x\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

$$(I)^2 = (E)^2\frac{C}{L}\left(2 + 2 \cos \frac{4\pi}{\lambda}x\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

These equations give us the numerical value of the maximum potential and current during the phase at any point in the cable.

We will apply them to certain instances. Let the length of the cable be one-quarter of a wave length, then when $x = l = \frac{\lambda}{4}$ we have (V) = 2(E), and $(I) = 0$. Also when $x = 0$ we have (V) = 0 and $I = 2(\mathrm{E})\frac{\sqrt{\mathrm{C}}}{\sqrt{\mathrm{L}}}$. Accordingly, in this case there is a steady increase of potential and decrease of current all the way from the origin to the open or free end of the cable. The distribution of potential may be represented by the ordinates of the dotted line in Fig. 4, where

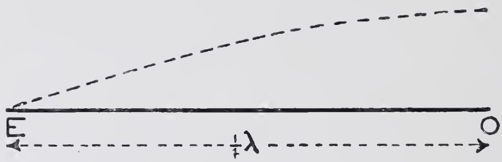


Fig. 4.—Distribution of Potential along a Finite Cable having a Simple Periodic E.M.F. placed at E (*Fundamental Oscillation*).

the thick black line represents the cable, E being the end at which the electromotive force is applied and O the free or insulated end of the cable.

Again, suppose we take the length of the cable equal to $\frac{3\lambda}{4}$. Then at the distances $x = 0, x = \frac{\lambda}{4}, x = \frac{\lambda}{2}, x = \frac{3\lambda}{4}$, we have (V) = 0, (V) = 2(E), (V) = 0, (V) = 2(E).

There are, therefore, loops and nodes of potential, and similarly loops and nodes of current. The current, however, is a maximum at those points at which the potential is zero, and *vice versâ*.

The distribution of potential may be represented by the ordinates of the dotted line in Fig. 5.

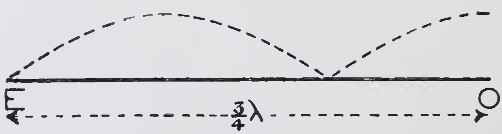


Fig. 5.—Distribution of Potential along a Finite Cable having a Simple Periodic E.M.F. placed at E (*First Harmonic Oscillation*).

In the same manner, if we take $l = \frac{5}{4}\lambda$ and examine the distribution of potential, we always find it to be a maximum at the free end O, whilst at that point the current is zero. Also the potential is a maximum at a distance $\frac{\lambda}{4}$ from the free end, and there are loops and nodes of potential separated by distances $\frac{\lambda}{4}$, as shown by the ordinates of the dotted line in Fig. 6.

If, then, the wire or conductor has a length which is any exact

multiple of one-quarter of a wave length, so that $l = M\frac{\lambda}{4}$ where M is any integer number, then it is easy to show that there will be $\frac{M+1}{2}$ loops of potential and the same number of nodes, including those at the beginning and end of the wire. Thus if $M = 1$ there is one loop at the free end and one node at the generator end; if $M = 3$ there are two loops and two nodes, and so on.

It is clear, therefore, that if a conductor has a length equal to some exact integer multiple of the quarter wave length of any harmonic electric oscillation, and if a simple periodic or sinoidal electromotive force having the corresponding frequency is applied at one end, we have *stationary electric waves* of potential and current set up on the wire, that is, a distribution of potential and current varying from point to point along the wire in accordance with the ordinates of a sine curve.

We may, if we please, consider that this is due to the interference of waves reflected at the open end of the wire with those which are travelling up the wire with a velocity $\frac{1}{\sqrt{CL}}$ from the source.

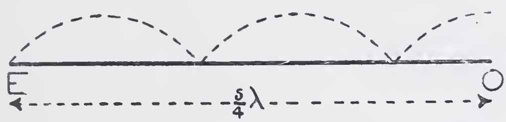


FIG. 6.—Distribution of Potential along a Finite Cable, OE, having a Simple Periodic E.M.F. placed at E (*Second Harmonic Oscillation*).

There is a perfect analogy between this electrical phenomenon and the stationary aerial waves produced in stopped organ pipes, the stopped end corresponding to the insulated end of the wire. Electric potential corresponds, then, to air pressure, and electric current to velocity of the air particles.

We may refer the reader to any good treatise on acoustics for a full description of the mode of production of these stationary air waves in open or closed pipes, and a knowledge of these acoustic effects is of assistance in comprehending the corresponding electrical phenomena. Otherwise we may compare the electric vibrations set up on wires or helices with the stationary waves produced in stretched cords when put in transverse vibration.

3. Effect of Damping upon the Stationary Waves on Wires.—If we do not neglect the damping or attenuation of the waves propagated along the finite wire, the expressions for the current and potential at any point become a little more complicated, but are easily obtained. Referring to equations (33) and (31) for the potential and current at any point in the insulated wire, we have—

$$V = E\left\{\epsilon^{-Px} + \epsilon^{-P(2l-x)}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

$$I = E\frac{\sqrt{K+jpC}}{\sqrt{R+jpL}}\left\{\epsilon^{-Px} - \epsilon^{-P(2l-x)}\right\} \quad . \quad . \quad . \quad (46)$$

If we put $P = \alpha + j\beta$, we then have—

$$V = E\Big[\Big\{\epsilon^{-\alpha x}\cos\beta x + \epsilon^{-\alpha(2l-x)}\cos\beta(2l-x)\Big\} - j\Big\{\epsilon^{-\alpha x}\sin\beta x + \epsilon^{-\alpha(2l-x)}\sin\beta(2l-x)\Big\}\Big]$$

This is a vector equation in the form $V = A + jB$.
If we scalarize or find the size of the vector, we have—

$(V) = \sqrt{A^2 + B^2}$, or by substitution

$$(V) = (E)\sqrt{\epsilon^{-2\alpha x} + \epsilon^{-2\alpha(2l-x)} + 2\epsilon^{-2\alpha l}\cos 2\beta(l-x)} \quad . \quad (47)$$

The above equation may be written—

$$(V) = (E)\epsilon^{-\alpha x}\sqrt{1 + \epsilon^{-4\alpha(l-x)} + 2\epsilon^{-2\alpha(l-x)}\cos 2\beta(l-x)} \quad (48)$$

If $x = l$, we have $(V) = 2(E)\epsilon^{-\alpha l}$.

In the same way, if we take the expression for I in (46) and write it out, we have—

$$I = E\frac{\sqrt{K + jpC}}{\sqrt{R + jpL}}\Big[\Big\{\epsilon^{-\alpha x}\cos\beta x - \epsilon^{-\alpha(2l-x)}\cos\beta(2l-x)\Big\} - j\Big\{\epsilon^{-\alpha x}\sin\beta x - \epsilon^{-\alpha(2l-x)}\sin\beta(2l-x)\Big\}\Big]$$

This is a vector expression of the form $\dfrac{\sqrt{a + jb}}{\sqrt{c + jd}}(e + jf)$, and hence, by the rule given on p. 259 for obtaining the size of such a vector, we have—

$$(I) = (E)\Big(\frac{K^2 + p^2C^2}{R^2 + p^2L^2}\Big)^{\frac{1}{4}}\sqrt{\epsilon^{-2\alpha x} + \epsilon^{-2\alpha(2l-x)} - 2\epsilon^{-2\alpha l}\cos 2\beta(l-x)} \quad (49)$$

If $x = l$, we have $(I) = 0$.

We may also write equations (48) and (49) in the form—

$$(V)^2 = (E)^2\epsilon^{-2\alpha x}\Big\{1 + \epsilon^{-4\alpha(l-x)} + 2\epsilon^{-2\alpha(l-x)}\cos 2\beta(l-x)\Big\} \quad (50)$$

$$(I)^2 = (E)^2\frac{\sqrt{K^2 + p^2C^2}}{\sqrt{R^2 + p^2L^2}}\epsilon^{-2\alpha x}\Big\{1 + \epsilon^{-4\alpha(l-x)} - 2\epsilon^{-2\alpha(l-x)}\cos 2\beta(l-x)\Big\} \quad (51)$$

In each of these expressions for the potential and current in the conductor at any point x, the quantity in the bracket consists of an exponential part which varies steadily with x, and a periodic or cosine term which varies periodically. This last term is more pronounced in its effect in proportion as β is large and α small. Hence, if we made the resistance of the cable per unit of length small and the inductance large, also if we increase the capacity and reduce the leakage per unit

of length as much as possible, we shall get more marked loops and nodes than if the inductance is small.

An important consequence follows from this. We can by coiling the wire into a spiral of a single layer of wire in closely adjacent turns increase the inductance per unit length of the spiral. The spiral wire acts like a linear conductor of abnormally large inductance, and hence the spiralization promotes the formation of marked loops and nodes.

Accordingly, the effect of large wire resistance or large insulation conductance per unit of length of the conductor is to damp out all evidence of loops and nodes or stationary waves on the wires. On the other hand, the effect of large inductance and capacity per unit of length of the conductor is to render more evident the phenomena of stationary electric waves.

4. Experimental Production of Stationary Electric Waves upon Spiral Wires.—The above theoretical investigation can be tested and beautifully illustrated by means of experiments carried out with insulated wire hellices on which stationary electric waves may be formed.

If we wind on a non-conducting rod a helix of insulated wire in one single layer of closely adjacent turns, we have a conductor which may be regarded as a cylindrical conductor having a certain capacity, inductance, resistance, and insulation per unit of length.

The length of the conductor is the length of the spiral, not the length of the wire forming it, and by capacity and inductance per unit length of the spiral is meant the whole capacity or inductance as it stands divided by the length of the spiral.

We have already seen that the inductance of a spiral of this kind can be nearly predetermined, if the ratio of length to diameter is large, by the formula—

$$L = \frac{\pi^2 D^2 N^2}{l}$$

where l is the length, D the diameter, and N the total number of turns on the spiral. Hence the inductance per unit of length is equal to $(\pi DN')^2$ where N' is the number of turns per unit of length of the spiral. Since the length of wire wound on one unit of length of the spiral is $\pi DN'$, we have the rule that the inductance of such a spiral per unit of length is numerically equal to the square of the length in centimetres of the wire wound on per unit of length of the helix. We can therefore make it large by employing a fine wire. Again, the capacity of such a helix is not much different from that of a metallic cylinder of the same external dimensions, and therefore not much affected by the size of the wire used. We can therefore increase the inductance per unit of length (L) without increasing the capacity per unit of length. Also, we can keep down the resistance per unit of length by using a wire of high conductivity, and we can make the insulation high by covering it with silk and winding the wire on an ebonite tube. By these means we can make a conductor of linear form, for which the constant $\alpha = \sqrt{\frac{RK}{2}}$ is small compared with $\beta = \sqrt{CL}$, and therefore, as above explained, the nodes and loops

will be sharply marked when stationary electric waves are formed upon it.

For this purpose a helix of insulated wire of the following dimensions is convenient:—

On an ebonite rod or thick tube 215 cms. long and 4·75 cms. in diameter and circular section is wound a helix of silk-covered copper wire, consisting of 5465 closely adjacent turns in one layer.

This helix of wire is 210 cms. in length, and each turn has a mean diameter of 4·78 cms. Hence the total inductance is $32 \cdot 07 \times 10^6$ cms., and the inductance per centimetre of length of the helix is $1 \cdot 527 \times 10^5$ cms. If this helix is placed in a horizontal position at a height of 50 cms. or so above a table supported on insulating stands, we can measure its capacity with respect to the earth, and for the helix above described it is found to be 45 micro-mfds.[1] Hence the capacity per unit of length C is $\frac{45}{210}$ micro-mfd.

An electric wave, therefore, travels along this spiral with a velocity of $\frac{1}{\sqrt{CL}}$, which in this case is $174 \cdot 8 \times 10^6$ cms. per second.

This velocity is about $\frac{1}{150}$th part of the velocity of light.

Hertz has described an experiment in which he established stationary electric waves on a spiral wire and compared the internodal distances with those which would be formed if the wire were stretched out straight, and he found that in the former case the velocity of the wave was much less than that of light.[2]

H. C. Pocklington has treated the matter theoretically, and he also shows that the velocity of the electric wave along a spiral is less than its velocity along the same wire stretched out straight. From the theory given above it is clear that this is due to the greatly increased inductance per unit of length of the spiral as compared with the simple linear wire.[3]

We can then proceed to set up stationary electric oscillations on the above-described spiral wire as follows: A condenser of variable capacity and a variable inductance are joined in series with each other and with a spark gap. For this purpose a condenser made as follows is convenient. Rectangular pieces of good sheet ebonite $20 \times 22 \cdot 5$ cms. and 3 mms. in thickness are coated on both sides with tinfoil, the area of each tinfoil sheet being $15 \times 17 \cdot 5$ cms. Twenty-four of these plates are prepared and grouped in six sections, each of four plates. The tinfoil sheets have tinfoil lugs attached to them, and in each set of four plates the tinfoils are so joined up as to make a condenser of nearly 0·001 mfd. capacity. The whole set of six condensers then has a capacity of 0·006 mfd., and they can be joined partly in series and partly in parallel. These six bundles of four ebonite plates are bound with silk and immersed in an ebonite box filled with vaseline oil free from water.

In a condenser so made by the author there were slight differences

[1] See J. A. Fleming, "On the Propagation of Electric Waves along Spiral Wires," *Phil. Mag.*, Oct., 1904, ser. 6, vol. 8, p. 433.

[2] See "Electric Waves," H. Hertz, English translation by D. L. Jones, pp. 158, 159.

[3] See H. C. Pocklington, "Electric Oscillations in Wires," *Proc. Camb. Phil. Soc.*, Oct. 25, 1897, vol. ix. p. 324.

in capacity between the six condensers, but when all were joined in parallel the measured capacity was 0·005835 mfd., and when the six were joined in two groups of three condensers, each in series, the two sets being in parallel, it gave a condenser of 0·001461 mfd. These capacities can be accurately determined by means of the revolving switch described in Chap. II., p. 170. The variable inductance may conveniently take the form of a helix of thick copper wire with movable contact, as described in Chap. II., p. 152.

The spark gap should consist of a pair of zinc balls adjustable as to distance. They should be enclosed in a wooden box to reduce noise and prevent stray light.

The spark balls S, condenser C, or condensers C_1 and C_2, and variable inductance L, are then joined up with the long insulated helix H, as shown diagrammatically in Fig. 7. The secondary terminals of an induction coil I are connected to the spark balls, and one spark ball, namely, that next to the inductance coil L, is connected to the earth, E, that is, to a gas or water pipe, by a wire. On

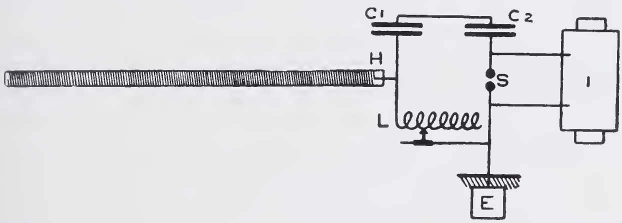


FIG. 7.—Arrangement for producing Stationary Electric Waves on a Long Helix, H, H, by the Oscillations in a Condenser Circuit possessing Inductance and a Spark Gap.

starting the induction coil oscillations are set up in the condenser circuit, the frequency n of which is given by the formula—

$$n = \frac{5 \times 10^6}{\sqrt{CL}}$$

The velocity W with which the wave travels up the helix is given by—

$$W = \frac{1}{\sqrt{C_1 L_1}} = n\lambda$$

where C_1 and L_1 are the capacity and inductance of the helix per unit of length.

Also for the production of stationary waves we must have the wave length λ of the stationary wave on the helix so adjusted that—

$$m\frac{\lambda}{4} = l$$

where m is unity or some odd integer number, and l is the length of the helix.

Combining these equations, we have—

$$W = \frac{1}{\sqrt{C_1L_1}} = \frac{5 \times 10^6}{\sqrt{CL}} \cdot \frac{4l}{m} \quad . \quad . \quad . \quad . \quad (52)$$

$$\text{or} \quad \sqrt{CL} = \frac{20l \times 10^6}{m} \sqrt{C_1L_1} \quad . \quad . \quad . \quad . \quad . \quad (53)$$

If, therefore, we adjust the *oscillation constant* $\sqrt{CL}$ of the condenser circuit to be equal to $20l \times 10^6 \times \sqrt{C_1L_1}$, divided respectively by 1, 3, 5, 7, we then shall find that when the oscillations are established in the condenser circuit, resonant stationary oscillations are set up on the helix.

These will show themselves by making strong electric brush discharges into the air at the insulated end of the helix, and at the loops or antinodes, and in a dark room the helix will be seen to be surrounded by a glow of light, which is brightest at the antinodes of potential. It can, however, be best detected and the position of the nodes fixed by holding a vacuum tube of the spectrum type filled with rarefied neon near the tube.

Neon is one of the rare atmospheric gases discovered by Sir William Ramsay, and Sir James Dewar has shown that it can be

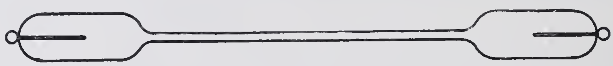


FIG. 8.—Neon Vacuum Tube.

extracted from it by absorbing the oxygen, nitrogen, and other commoner constituents of air by means of cocoanut charcoal cooled with liquid hydrogen or liquid air. The author found some time ago that a vacuum tube of the spectrum type with a very small bore, not more than 1 mm. in the straight part of the tube (see Fig. 8), when filled with rarefied neon, formed an excellent and most sensitive means of detecting a high frequency electric field. The tube then glows with a bright red-orange light, which is visible in broad daylight. If such a tube cannot be obtained, then one of the same form, made with uranium glass and filled with rarefied carbonic dioxide gas, will answer the purpose fairly well.

To locate the loops and nodes, the vacuum tube must be held over the helix and perpendicular to it, and at varying distances from it, and moved along parallel to itself. It will then be found that in some positions it glows brightly, whilst in others it does not, and a very slight movement on either side of the last positions will make the tube illuminate again. These non-glowing positions are just over the nodes of potential on the helix. If a boxwood scale divided into centimetres and millimetres is placed below the helix and at about 10 cms. from it, it is possible to read off the distance from the end of the helix at which these antinodes and nodes of potential exist, as shown by the positions at which the neon or other vacuum tube glows or does not glow brightly. We can then adjust the inductance in the condenser circuit and the capacity of the latter, until we so arrange matters that we have a good electric brush at the end of

the helix farthest from the condenser, and either no node or else 1, 2, 3, 4, etc., nodes of potential, indicating that the helix has established on it either its fundamental or its 1st, 2nd, 3rd, etc., harmonic oscillation, as shown by the existence of $\frac{1}{4}$ of a stationary wave or $\frac{3}{4}$, $\frac{5}{4}$, $\frac{7}{4}$, etc., stationary waves.

In a research of this character the author found that, with a helix as above described, the nodes and antinodes of potential were distributed as shown by the ordinates of the dotted lines in Fig. 9. The numbers given underneath the diagram OE representing the helix show the internodal distances in centimetres, and the distance of the first potential node from the open end O of the helix. Two things are at once noticeable.

(1) The internodal distances are not equal, but increase towards the end of the helix which is attached to the condenser. This seems to show that the velocity of the wave is not the same at all parts of the helix, but is rather greater near the condenser end E. This may be due to the free ends of the helix having a slightly smaller inductance per unit of length than the middle portions.

(2) The distance from the open end of the helix O to the first node of potential N_1 is always less than half the distance N_1N_2 between the two succeeding nodes, or any pair of succeeding nodes. In fact, the distance ON_1 multiplied by 2·5 is always nearly equal to N_1N_2.

The velocity of the wave along the helix can be ascertained by measuring the wave length of the stationary wave on the helix, which is equal to twice the distance N_1N_2 between the first and second nodes, and also ascertaining the frequency of the oscillations.

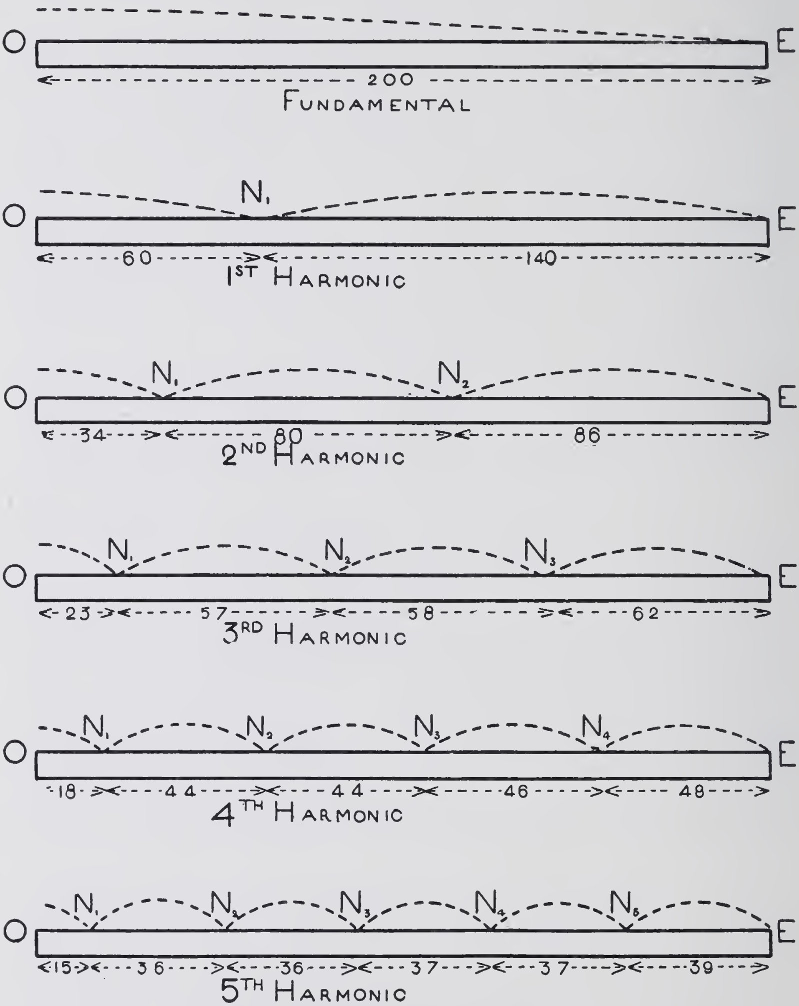
The frequency can be ascertained from the condenser capacity and the inductance in the main oscillating circuit. In experiments by the author[4] the real value of the inductance used corresponding to certain scale readings of the variable spiral inductance employed was carefully ascertained by comparing it with the inductance of certain squares of copper wire of known size. In this way a series of observations was made, noting the capacity C in the condenser circuit, the inductance L, the calculated frequency n, the observed stationary wave length λ on the helix, and from these data the velocity of the wave (W) was calculated. The results are shown in the table below.

Oscillation.	Capacity in mfds. in condenser circuit, C.	Inductance in cms. in condenser circuit, L.	Calculated frequency, n.	Observed wave length, λ.	Calculated wave velocity, $W = n\lambda$.
Fundamental . .	0·005835	110,000	$0{\cdot}197 \times 10^6$	(871)	(172×10^6)
1st harmonic . .	0·002887	25,000	0·588 ,,	292	172 ,,
2nd ,, . .	0·001461	18,000	0·977 ,,	175	172 ,,
3rd ,, . .	0·001464	9,000	1·379 ,,	124	171 ,,
4th ,, . .	0·001461	6,000	1·70 ,,	95	163 ,,
5th ,, . .	0·001461	5,000	1·9 ,,	80	152 ,,

It will be seen that for the first three harmonics the wave velocity

[4] See J. A. Fleming, "On the Propagation of Electric Waves along Spira Wires," *Phil. Mag.*, Oct., 1904, ser. 6, vol. 8, p. 417.

is nearly 172 × 10^6 cms. per second, and this agrees very well with the velocity 174 × 10^6 cms. per second calculated from the measured inductance and capacity of the spiral per unit of length. There is,



LENGTHS IN CMS.

FIG. 9.—Diagrams representing the Stationary Potential Waves set up on a Long Helix, OE, by a High Frequency E.M.F. applied at one End, E. The Distance of the Dotted Lines from the Helix represents the Potential Amplitude at that Point of the Helix.

however, a falling off in the value of W for higher harmonics. This may be due to inaccuracy in measuring the small values of the inductance L or else to some cause not yet ascertained.

Two points call for notice. If we employ the velocity, viz. 172×10^6 cms. per second, obtained from observation made on the wave lengths of the first, second, and third harmonics to calculate back the wave length of the fundamental oscillations, we find this last to be 871 cms. The length of the helix was 210 cms. Hence it is clear that the fundamental wave length is rather more than four times the length of the helix.

In the next place the distance from the open end of the helix to the first node of potential is always decidedly less than one quarter of the corresponding wave length, that is, it is less than half the distance between the two succeeding nodes of potential. In fact, the wave length is more nearly equal to *five times* the distance from the open end to the first node.

This indicates that the simple theory above given is not sufficient to fit the facts. A more complete theory of the production of stationary electric waves on open circuits has been given by Professor H. M. Macdonald.[5] In this investigation he shows that if the fundamental electrical oscillation is set up on a perfectly straight insulated wire, it consists in an oscillation such that the centre of the wire is a node of potential and the two extremities are antinodes, but the wave length of the oscillation set up is shown to be not simply twice the length of the wire, as the simple theory given in § 4 of this chapter would indicate, but 2·53 times the length of the wire. Hence this indicates that if a wire has a high frequency electromotive force applied at one end and the length of the wire is so adjusted that there is an antinode of potential at the other end, the wire vibrating in its fundamental oscillation, then the length of the wave must be nearly five times that of the wire. It is impossible to verify this with the fundamental oscillation of a single wire, because we cannot make a sufficiently sharp measurement of the position of the node, but in the case where the wire has a higher harmonic oscillation produced upon it, as in the experiments of the author above described with the spiral, we can ascertain the length of the wave by measuring the distance between the first and second node, and then ascertain also the distance from the first node to the open end of the wire, and we find, as shown in the diagram in Fig. 9, that the distance from the end of the wire to

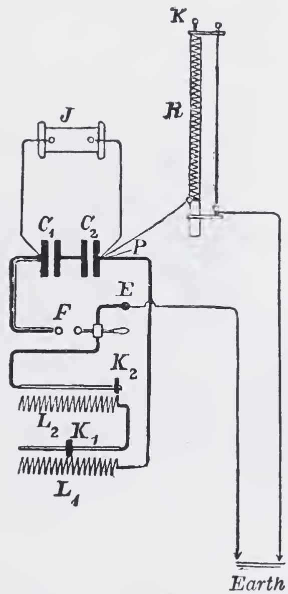


Fig. 10. — Arrangement of Seibt's Apparatus for exhibiting Stationary Potential Waves on a Vertical Helix. J, induction coil; C_1, C_2, condensers; F, spark balls; L_1, L_2, adjustable inductances; R, helix.

[5] Adams' Prize Essay, by H. M. Macdonald, "Electric Waves," Cambridge University Press, 1902, see p. 111.

the first node is to the distance between the first and second nodes very nearly in the ratio of the numbers 2 to 5.

It will be seen, by referring to Fig. 9 delineating the above described experiments with stationary waves on spiral wires, that for the second harmonic the ratio of ON_1 to N_1N_2 is 34 to 80, which is exactly as 2 to 5, and for the third harmonic the ratio of ON_1 to N_1N_2 is as 23 to 57, which are also very nearly as 2 to 5, and the same with the fourth and fifth harmonics.

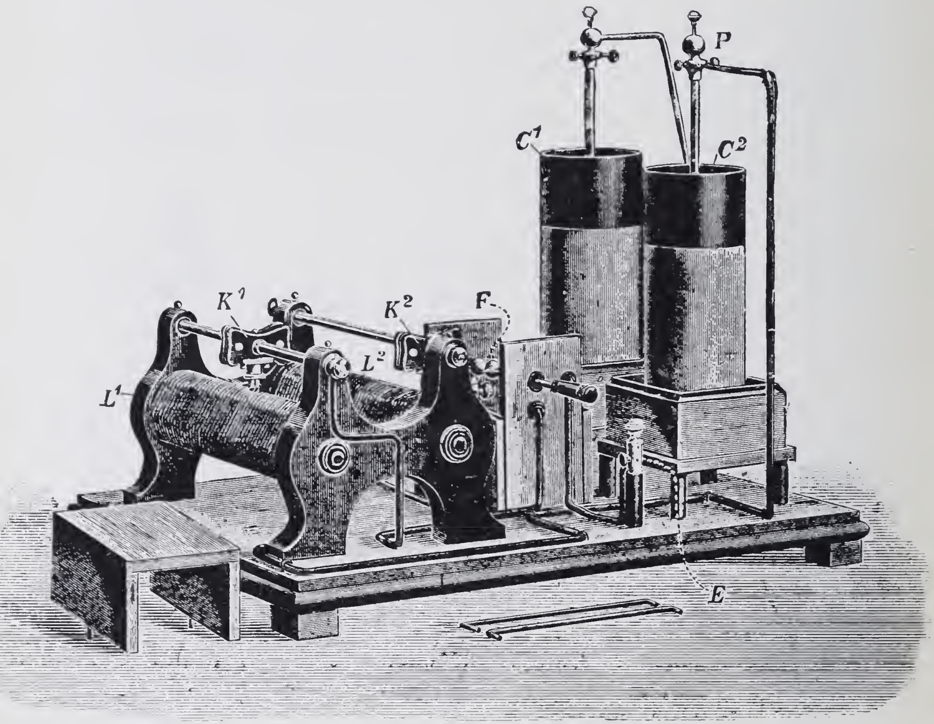


FIG. 11.—Perspective View of Condenser Circuit of Seibt's Apparatus, as made by F. Ernecke of Berlin. C^1, C^2, Leyden jars; F, spark balls in a box; L^1, L^2, variable inductance coil.

These observations, therefore, with the spiral so far confirm Macdonald's theory.

Another method of exhibiting these nodes and loops on a spiral wire was devised by G. Seibt.[6]

Seibt's method is to place a spiral of insulated wire wound on a wooden rod in a vertical position and to stretch alongside of it and parallel to it, a few centimetres away, a very fine bare wire which is connected to the earth. The spiral is connected at bottom end

[6] See "Elektrische Drahtwellen," *Elecktrotechnische Zeitschrift*, April 10, 17, 24, May 1, 8, 1892, vol. xxiii.

to an oscillating circuit consisting of a couple of Leyden jars, a spark gap, and a variable inductance, and oscillations are excited in this as usual by an induction coil. The apparatus is as represented in Figs. 10 and 11.

When oscillations are set up in the Leyden jar circuit, and the inductance varied so as to give the frequency of these oscillations the proper value for exciting either the fundamental or the higher harmonic oscillations in the spiral, then an electric brush discharge takes place between the surface of the spiral and the parallel earth wire (see Fig. 12).

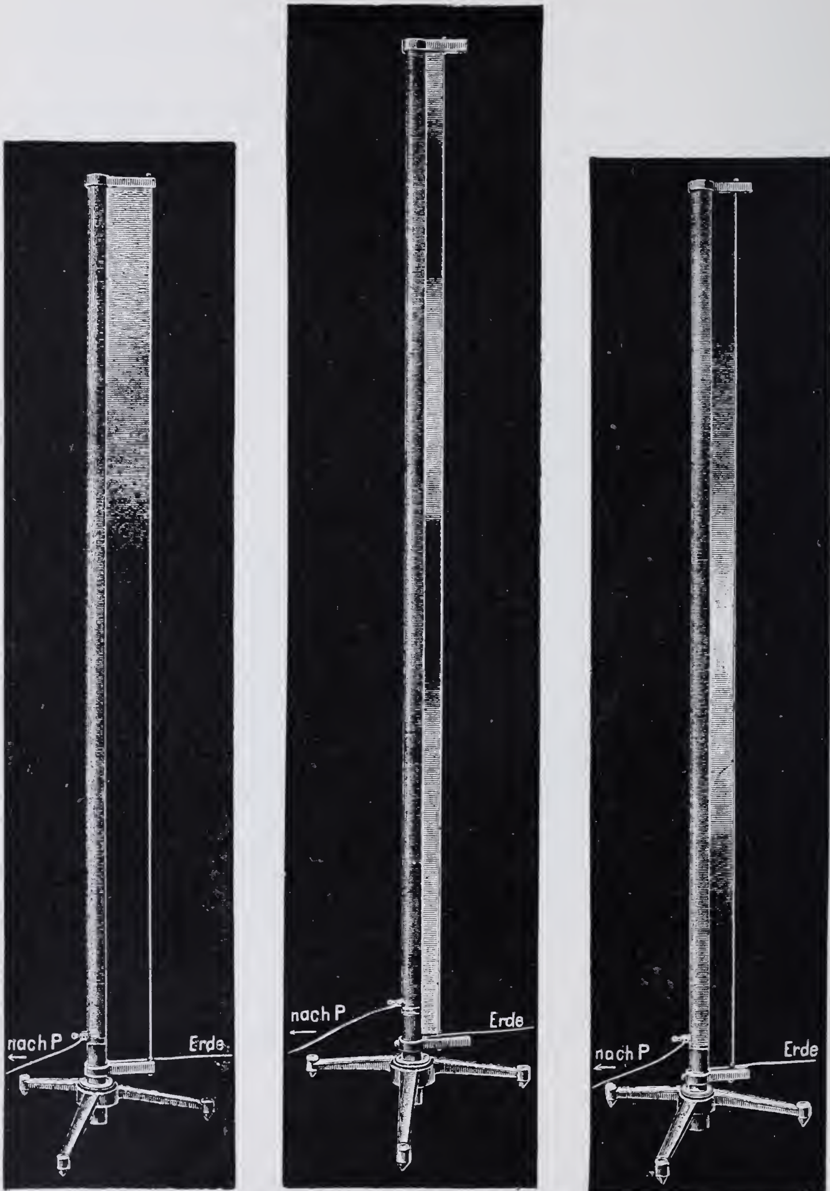
If the spiral is vibrating in its fundamental manner, then its glow is very brilliant at the top, and drops away to nothing down at the bottom; but if it is vibrating in its higher harmonics, then the glow is distributed in patches, the brightest points marking the position of the antinodes of potential. This experiment forms a very beautiful one, but it can only be seen in a perfectly dark room. Moreover, the position of the nodes and antinodes cannot be fixed with great accuracy, but it serves to render visible, in a sense, these stationary waves. Again, if a brass rod terminating in a knob is taken in the hand and the knob held near the top of the spiral when vibrating in its fundamental manner, very long thin sparks can be drawn from it, and a strong electric brush proceeds from the end of the helix. If the knob at the end of the rod is carried down the spiral, it will be found that the spark drawn becomes shorter but more brilliant as it is taken lower down.

This indicates the gradual decrease in the potential amplitude as we pass from the open or insulating end of the spiral to the condenser end, and also it indicates the gradual increase of the current, the current flowing into the helix being a maximum at the lower end of the spiral and the potential amplitude a maximum at the upper end.

It will be seen, therefore, that to excite the fundamental oscillation in the spiral we must apply to the bottom end a high frequency electromotive force, the frequency of which is such that the wave produced by it travels a distance rather more than four times the length of the spiral during the time of one period. We have seen that the velocity with which the wave travels along the spiral is measured by $\frac{1}{\sqrt{C_1L_1}}$, where C_1 is the capacity of the spiral per unit of length and L_1 is its inductance, hence the frequency n required to produce the fundamental oscillation is given by the equation—

$$n = \frac{1}{\lambda\sqrt{C_1L_1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

In the above expression λ is the wave length of the fundamental oscillation, which, according to the simple theory, is four times the length of the spiral, and, according to Macdonald's theory, five times the length of the spiral; but, as far as the experiments of the author go, is, in fact, nearly 4·15 times the length of the spiral. Hence we may say that the frequency n_0 required to produce the fundamental oscillation on a spiral of length l is given by the equation—



(a) (b) (c)

FIG. 12.—Electric Glow Discharge between a Vertical Earth Wire and a Seibt Helix when connected to a Condenser Circuit yielding High Frequency Oscillations. (*a*) Helix exhibiting fundamental oscillation (upper end insulated); (*b*) helix exhibiting second harmonic oscillation (upper end insulated); (*c*) helix exhibiting fundamental oscillation (upper end earthed).

$$n_0 = \frac{1}{4 \cdot 15 l \sqrt{C_1 L_1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

The frequency required to produce the first harmonic, or the oscillation having one node about one-third of the way from the open end of the spiral, is $3n_0$. If we call this n_1 we have for the frequency required to produce the first harmonic the expression—

$$n_1 = \frac{1}{12 \cdot 45 l \sqrt{C_1 L_1}} \cdot \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (56)$$

In the same way the frequency n_2 required to produce the second harmonic is five times, the third harmonic seven times, that required to produce the fundamental oscillation, and, generally speaking, the frequency required to produce the mth harmonic is $(2m + 1)$ times the frequency of the fundamental. Therefore we have, for the frequency n_m required to produce the mth harmonic on the spiral or state of electrical vibration with m modes of potential, the expression—

$$n_m = \frac{1}{4 \cdot 15(2m + 1) l \sqrt{C_1 L_1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

The author has found that winding the spiral on a wooden rod is a mistake. Ordinary wood, even if dry, has considerable conductivity for high frequency currents, and therefore tends to give the spiral a greater capacity as the frequency increases. This creates a disagreement between the observed facts and the deductions from theory.

The helix must be wound on either an ebonite or a glass rod. In a subsequent chapter (Chap. VI.) we shall see how such a helix may be used as a cymometer for measuring the length of the electric waves radiated from an aerial wire as used in wireless telegraphy.

5. Direct, Inductive, and Electrostatic Coupling.—In establishing stationary electric waves upon wires, a high frequency electromotive force must be created in the wire at some point. This may be done in one of three ways, which are respectively called the *direct*, *magnetic* or *inductive*, and *electrostatic* or *dielectric coupling*.

The direct coupling consists in connecting a wire on which it is desired to establish the stationary waves directly to some point on an oscillating circuit which is rising and falling rapidly in potential; or we may connect two similar wires to two points on an oscillating circuit which vary oppositely in potential at the same moment. The simplest illustration of this is to connect to the inner and outer coating of a Leyden jar two long wires which are extended horizontally. When the jar is discharged (see Fig. 13) oscillations are set up and the coatings of the jar rise and fall rapidly in potential in opposite senses. Hence the wires have periodic electromotive impulses applied to their ends. Just as when a rope fixed at one end is jerked at the other and a hump or wave runs along it, so in the case of the electric wires a wave of potential travels along the wire and is reflected at the insulated end and runs back. The velocity with which the wave runs

along the wire if straight is the velocity of light. We have seen (see Chap. II., equation 91) that the electrostatic capacity of a long

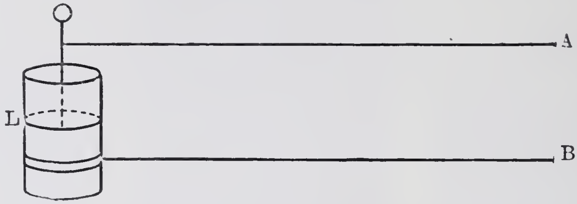


FIG. 13.—L, Leyden jar having inner and outer coatings, connected to resonant wires, A, B, of proper length. (Lodge.)

circular-sectioned wire of diameter d and length l in free space is nearly given by the expression—

$$C = \frac{l}{2 \log_\epsilon \frac{2l}{d}} \text{ (in electrostatic units)} \quad . \quad . \quad . \quad (58)$$

In electromagnetic measure it is obtained by dividing the above expression by the numerical factor 9×10^{20}. Hence—

$$C = \frac{l}{9 \times 10^{20} \times 2 \log_\epsilon \frac{2l}{d}} \text{ (in electromagnetic units)} \quad . \quad (59)$$

The number 9×10^{20} is the square of the electromagnetic velocity u, identical with the velocity of light.

The inductance L of such a wire in electromagnetic units is given by—

$$L = 2l\left(\log_\epsilon \frac{4l}{d} - 1\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (60)$$

We may write the above equation in the form—

$$L = 2l\left(\log_\epsilon \frac{2l}{d} + \log_\epsilon 2 - 1\right) \quad . \quad . \quad . \quad (61)$$

$$\text{or} \quad L = 2l\left(\log_\epsilon \frac{2l}{d} - 0{\cdot}3\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (62)$$

If $\frac{2l}{d}$ is large compared with 0·3, we can say that for this wire—

$$L = 2l \log_\epsilon \frac{2l}{d}$$

$$\text{and hence} \quad \sqrt{CL} = \frac{l}{3 \times 10^{10}}$$

$$\text{or} \quad \frac{1}{\sqrt{\frac{C}{l} \cdot \frac{L}{l}}} = 3 \times 10^{10} = u$$

The left-hand side of the above equation is the reciprocal of the square root of the product of the capacity and inductance of the wire per unit of length, and this, we have seen, is the expression for the velocity with which the electric wave runs along the wire. The symbol u stands for the number 3×10^{10}, or the velocity of light in centimetres per second. Therefore the wave runs along the straight wire with the velocity of light. It is reflected at the open end, and if the frequency is adjusted so that the time taken by the wave to travel nearly four times the length of the wire is equal to one complete period of the electromotive force, then stationary waves are produced on the wire and a greatly exalted potential amplitude occurs at the open end.

If the frequency is 3, 5, 7, etc., times this fundamental frequency, then higher harmonic oscillations with nodes and antinodes of potential are formed on the wire.

One of the first investigators to notice and measure these stationary waves on wires so produced by direct coupling with the coatings of a Leyden jar was Sir Oliver Lodge.[7]

Let a condenser of capacity C be discharged through a low resistance circuit of inductance L, and let two long wires proceed parallel to each other and insulated in space from each other, one end of each being connected to one coating of the condenser. The capacity C_1 of the two wires in electrostatic units with respect to each other can be shown to be given by the equation [8]—

$$C_1 = \frac{l}{4 \log_\epsilon \frac{2D}{d}} \text{ (in electrostatic units)} \quad . \quad . \quad . \quad (63)$$

where l is the length of each of the wires, D their distance apart, and d the diameter of each wire assumed to be of circular section.

Hence the capacity in electromagnetic units is—

$$C_1 = \frac{l}{u^2 4 \log_\epsilon \frac{2D}{d}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (64)$$

The high frequency inductance L_1 of these two wires, each of length l, and at a distance D cms. apart in air, has beeen shown (see Chap. II. § 3 (55)) to be given by the expression—

$$L_1 = 4l\left(\log_\epsilon \frac{2D}{d}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

Hence, multiplying (64) and (65), we have—

$$C_1 L_1 = \frac{l^2}{u^2}, \text{ or } u = \frac{1}{\sqrt{\frac{C_1}{l} \cdot \frac{L_1}{l}}} = 3 \times 10^{10}$$

[7] See O. J. Lodge, "On the Theory of Lightning Conductors," *Phil. Mag.*, August, 1888, ser. 5, vol. 26, p. 217; also *The Electrician*, August 10, 1888, vol. xxi. p. 435.

[8] See "Handbook for the Electrical Laboratory and Testing Room," J. A. Fleming, vol. ii. p. 121.

The expression $\dfrac{1}{\sqrt{\dfrac{C_1}{l} \cdot \dfrac{L_1}{l}}}$ is the velocity of the wave along the wires, and is therefore equal to the velocity of light.

If, then, the capacity of the wires with respect to each other is small compared with that of the condenser, the discharge of the latter applies to the ends of the wires a periodic potential difference with a frequency $n = \dfrac{1}{2\pi\sqrt{CL}}$. In order that the stationary oscillations may be set up on the wire we must have for the fundamental oscillation such a length l for each wire that $u = 4ln = 3 \times 10^{10}$, and therefore—

$$l = \frac{\pi}{2} \times 3 \times 10^{10} \times \sqrt{CL}$$

In the above equation C is the capacity of the condenser in electromagnetic measure. If we express the condenser capacity in microfarads, and the inductance of the circuit through which it is discharging in centimetres, then we have the following very approximate formula :—

$$l = 1500\sqrt{C_{\text{mfds.}} \times L_{\text{cms.}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

Thus, for instance, let a small Leyden jar having a capacity of about $\frac{1}{700}$ mfd. be discharged through a loop of thick copper wire about 4 mms. in thickness and 120 cms. long. The inductance of this circuit would be about 700 cms., and the corresponding length l of the resonant wire would be 15 ms., or nearly 50 feet. Such a length of wire, if attached to the jar inner coating, would have the fundamental oscillation set up on it, and at the far end we should have an antinode of potential and a strong brush discharge.

Hence to exhibit nodes and loops of potential on a straight wire we need higher frequency, and therefore smaller capacity and inductance in the discharge circuit.

To establish the first harmonic oscillation with one node at about one-third the length of the wire from the open end, we must have a frequency three times that required for the fundamental, that is, the product CL must be nine times as great. Accordingly, if C is made four times greater, L must be made $2\frac{1}{4}$ times greater than would be the case to excite the fundamental.

These higher harmonic oscillations are, however, better called into existence by using an arrangement due to Hertz, and modified by other workers, such as Sarasin and de la Rive and Lecher.

6. Creation of Stationary Electric Waves on Straight Wires.—A convenient method of establishing stationary electric waves on wires is one which Continental writers generally attribute to Lecher, and call the Lecher arrangement. As a matter of fact, it originated with Lodge and Hertz, whilst Sarasin and de la Rive gave it an improved form.

Hertz devised the form of oscillator we shall describe more in detail in the next chapter, which consists of two metal plates having rods attached, these rods being terminated in spark balls. The rods

and plates are placed in one line, with the balls near together. They then constitute a condenser, with air as dielectric, which discharges across the gap when the potential difference of the plates, created by attaching the spark balls to the secondary terminals of an induction coil, exceeds a certain value determined by the width of the spark gap. This discharge sets up oscillatory currents in the rods and rapid oscillations of potential in the plates. If then two other plates are placed close to the plates of the oscillator, these first named having long parallel wires attached to them (see Fig. 14) with their ends insulated, we have the so-called Lecher arrangement.

Hertz used in some experiments only one extra plate and wire,[9] but Sarasin and de la Rive made the arrangement symmetrical by employing two plates and two parallel wires, whilst R. Blondlot showed that oscillations could be set up in a long wire circuit by

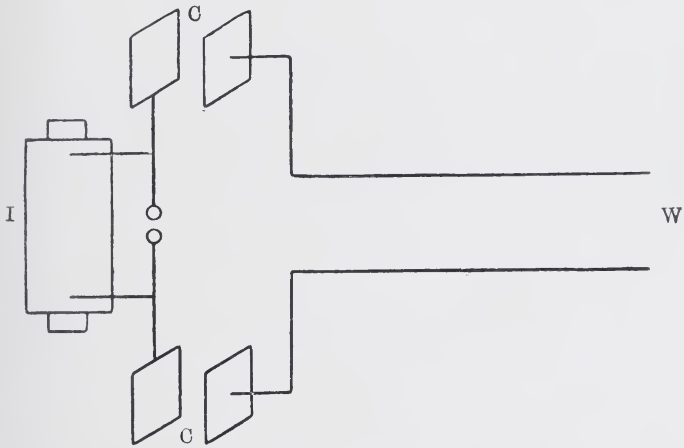


FIG. 14.—Lecher Arrangement for creating Stationary Electric Waves on Parallel Wires. The two open circuits are coupled electrostatically. I, induction coil; C, C, condenser plates; W, parallel wires.

coupling it electromagnetically with a circuit containing a condenser in which oscillations were created by a discharge across a spark gap.[10]

The double plate and parallel wire arrangement was also described by E. Lecher.[11] In this case the wires are said to be coupled electrostatically to the Hertz oscillator. When the secondary terminals of an induction coil are connected to the spark balls of the oscillator, and vibrations excited, the plates at the end of the wires are rapidly alternated in potential, and this, therefore, applies to the ends of the wires an alternating electromotive force; which in one wire may be

[9] See H. Hertz, "Electric Waves," English translation by D. E. Jones, p. 108, or *Wied. Ann.*, 1888, vol. 34, p. 551.

[10] See R. Blondlot, "Sur un nouveau procédé pour transmettre des ondulations électriques le long de fils metalliques," *Comptes Rendus*, 1892, vol. 114, p. 283.

[11] See E. Lecher, "Eine Studie über electrische Resonanzerscheinungen," *Wied. Ann*, 1888, vol. 41, p. 850.

represented by V cos pt and that to the other by $-$V cos pt. These electromotive forces create electric waves of potential which travel along the wires, as above proved, with the velocity of light, and if the wires are of suitable length compared with the frequency of the oscillations, the interference of the direct and reflected waves establishes stationary waves of potential and current on the wires. Lecher, following a method suggested by Dragoumis,[12] employed a vacuum tube laid across the wires like a bridge to detect the position of the nodes. The tube may be without the usual electrodes, and contain rarefied nitrogen with a trace of turpentine vapour. The author has, however, found that a tube filled with rarefied neon is much better as an indicator.

When the vacuum tube is placed at a node of potential it remains dark, but when placed at an antinode it glows. Lecher also found that if the vacuum tube was placed permanently at the end of the parallel wires it could be caused to glow, or not to glow, by moving about on the parallel wires another transverse wire placed as a bridge across them. This, however, introduces a complication. At first sight, it might appear that the positions at which the bridge wire must be placed not to affect the glow in the tube should depend solely upon the frequency of the oscillator. Experiments by H. Rubens[13] showed, however, that the position of the bridge at which the glow of the vacuum tube was brightest or extinguished did not depend upon the time period of the oscillator.

This is only one instance out of a number in connection with this subject which shows that the phenomena cannot be rightly interpreted unless we bear constantly in mind that, as already explained, the oscillations of an open circuit radiator, like a Hertz oscillator, subside with great rapidity. They are damped chiefly owing to dissipation of energy by radiation. On the other hand, if a circuit is nearly closed, the oscillations in it are very persistent. Hence, if an open circuit radiator, like that of Hertz, acts on a nearly closed circuit, the radiator, when in action, merely administers to the receiver, or resonant circuit, a sort of blow or electro-magnetic impulse at each discharge. The oscillations excited in the resonant circuit are those of its own free period, and not those forced on it by the radiator.

If we consider the bridge wire put across at any place transversely to the parallel wires, it creates two oscillation circuits. One of these consists of the two condensers, which are formed by the two plates of the Hertzian oscillator and the other two plates respectively in opposition to them, together with the rods of the Hertzian oscillator, and also the bridge wire and the included portion of the parallel wires. This circuit is denoted in Fig. 15 by the letters SC_1XYC_2. The other circuit consists of the bridge wire and the remainder of the parallel wires, and is denoted by AXYB (see Fig. 15). The magnitude of these circuits is dependent upon the position of the bridge wire. Experiment shows, then, that what takes place is as follows: When the Hertzian oscillator is excited, oscillations take place in the circuit SC_1XYC_2, and these excite other oscillations in

[12] See *Nature*, vol. 39, p. 548.

[13] See H. Rubens, *Wied. Ann*, 1891, vol. 42, p. 154; also see J. J. Thomson, "Recent Researches in Electricity and Magnetism," p. 462.

the circuit AXYB. The condition which must hold good for these last oscillations is, that the free extremities A and B of the wires must be antinodes of potential and of opposite sign. Hence, if we

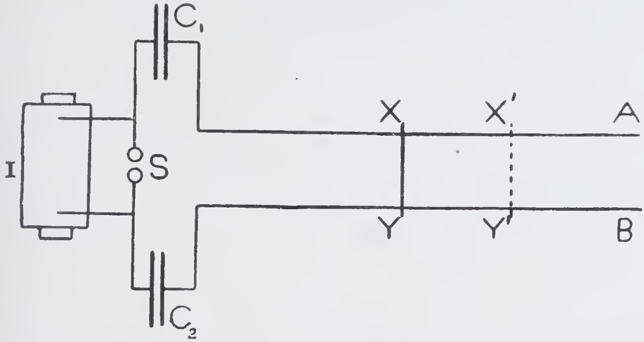


FIG. 15.—Lecher Wires bridged across and divided into Two Syntonic Circuits. I, induction coil; C_1, C_2, air condensers; A, B, Lecher wires; S, spark balls.

consider the wire AXYB stretched out straight, the oscillations of potential on it that are possible are indicated by the diagrams in Fig. 16. The length of the circuit AXYB must, therefore, be equal to some odd multiple of half the stationary wave length, in order that

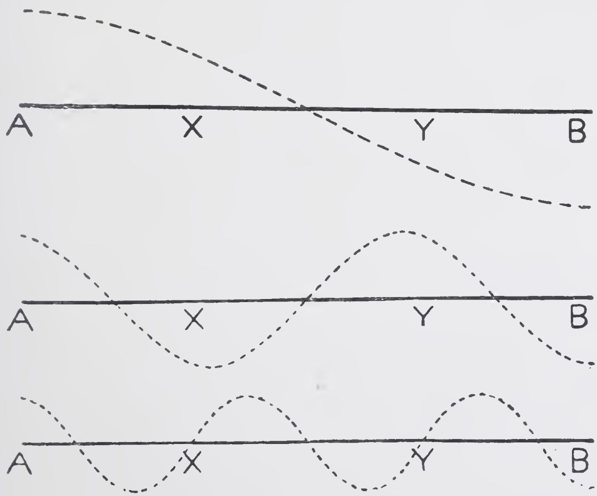


FIG. 16.—Possible Stationary Oscillations which can be created on the Section AXYB of a Lecher Circuit, as shown in Fig. 15. The distance of the dotted line from the firm line represents the potential amplitude at that point.

we may have the necessary conditions fulfilled, which are, first, that the centre of the bridge wire XY, that is, the central point of the circuit AXYB, shall be a node of potential, and the two extremities

A and B shall be antinodes, and at any instant have opposite potentials. Therefore the distance between two positions of the bridge wire XY, say at XY and X′Y′ (see Fig. 15), at which the vacuum tube shines equally brightly, is equal to one-half of the length of a stationary wave on the circuit AXYB. This wave length is determined by the length of the wire itself, and not that of the other exciting circuit.

On the other hand, to set up strong oscillations in the circuit AXYB, the frequency of the oscillations in the other circuit, SC_1XYC_2, must be so adjusted that the two circuits are in resonance. It follows, therefore, that to excite an oscillation on the wires, such that there shall be an antinode of potential at A and B, and one node only, at the centre of the bridge XY, the frequency n of the oscillations in the other circuit must be so adjusted that—

$$n = \frac{3 \times 10^{10}}{2\ (\text{the length of AXYB})} \quad . \quad . \quad . \quad . \quad (67)$$

The numeric which occurs in the denominator, viz. 2, is, in fact, a little more than 2, very nearly 2·5, because the length of the fundamental wave length of a linear oscillator is 2·5 times its length nearly, and not simply twice its length.

If, then, the vacuum tube is placed across the ends AB of the parallel wires, and the bridge XY moved to different positions, the tube glows most brightly for certain positions of the bridge. The condensers formed of the pairs of plates at the ends of each wire have a certain capacity, and this may be considered to be reckoned in its equivalent in length of straight wire. We might, in fact, replace the nearly closed oscillating circuit SC_1XYC_2 by an open circuit consisting of a wire bent twice at right angles.[14] The actual Lecher circuit is, therefore, equivalent to two pieces of wire, each bent twice at right angles, and having their central portions in common. Experiment, then, shows that if oscillations are set up in one part, they will create vigorous oscillations in the other part, if the lengths of the two circuits are in the ratio of any pair of the odd integer numbers. Experiments made by H. Rubens fully confirm this deduction,[15] and they show that we must not consider the phenomenon to consist simply in oscillations having the period due to the Hertz oscillator alone being forced on the long wires, and the bridge merely non-effective when placed at the nodes of potential so formed, but we have to consider the bridge as a common part of two circuits, in one of which oscillations are set up with a certain period, whilst others are created in the adjacent circuit, provided this is made to be of such a length that one of its natural periods of oscillation is in agreement with those of the primary circuit.

Another method of setting up oscillations in wires is due to M. Blondlot.[16] In this a circular wire circuit, of which the inductance

[14] See E. Lecher, *Wied. Ann.*, 1890, vol. 41, p. 850.

[15] See H. Rubens, *Wied. Ann.*, 1889, vol. 37, p. 529. For an account of these experiments in English, see J. J. Thomson's book, "Recent Researches in Electricity and Magnetism," pp. 461–467.

[16] Blondlot, *Journal de Physique*, ser. 2, vol. x. p. 549.

can be calculated, has inserted in it a spark gap and a condenser of known capacity. Surrounding this circular circuit, and in close contact with it, but separated by an insulator, is a second circuit consisting of one long wire (see Fig. 17). The oscillations in the condenser circuit act inductively on the wire circuit, and if the length of this last is properly adjusted, create stationary oscillations in it. By means of

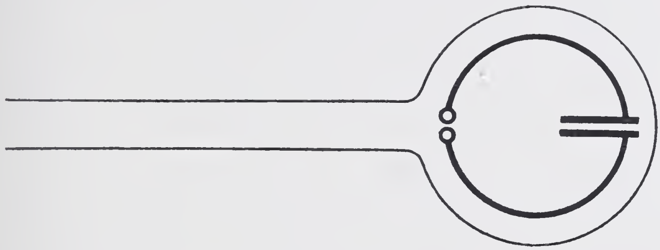


FIG. 17.—Blondlot's Mode of Inductive Coupling of an Open and Closed Oscillation Circuit.

the arrangement of this kind Blondlot was able to make a satisfactory determination of the velocity of propagation of an electric wave along a wire, and prove experimentally that it was identical with the velocity of light.

One of the most complete investigations on this matter was conducted by Professor Trowbridge and Mr. Duane.[17] In this work the

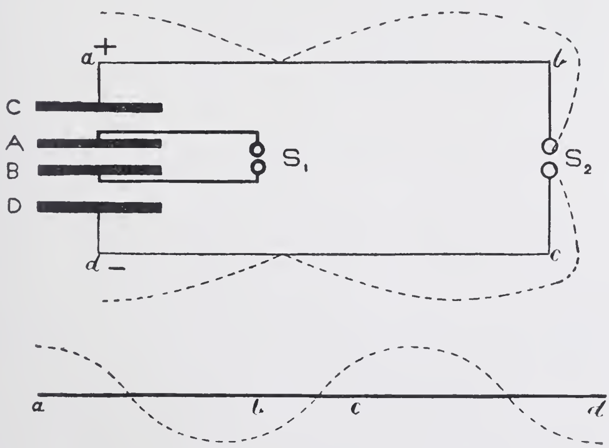


FIG. 18.—Trowbridge and Duane's Experiments on the Velocity of Electric Wave Propagation along Wires.

authors set up a nearly closed wire circuit, terminating in condenser plates A, B (see Fig. 18), having a small spark gap, S_1, in a symmetrical position in it. The terminal plates were in apposition to two other

[17] See Trowbridge and Duane, "On the Velocity of Electric Waves," *Phil. Mag.*, August, 1895, ser. 5, vol. 40, p. 211; also see J. A. Fleming, "The Alternate Current Transformer," vol. i. 3rd ed. p. 499.

condenser plates, C, D, which formed the condenser of a secondary oscillation circuit. Hence the two circuits were connected electrostatically. The frequency of the oscillations was then adjusted until stationary electric waves formed on the wire; the median point at the spark gap S_2 being a potential node, and one other node existing on each side of it between the central node and the terminal plates. This distribution of potential is indicated by the dotted lines in Fig. 18. By photographing the secondary spark the frequency of the oscillations was obtained, and by measuring the distance separating the two nodes lying on either side of the median node S_2 the semi-wave length was obtained. The velocity of the wave then became known. The mean of a large number of closely concordant observations gave the velocity of the wave along the wire as $3{\cdot}003 \times 10^{10}$ cms. per second. This is very close to the best determination of the velocity of light.

It may be taken, therefore, as definitely proved, both by theoretical reasoning and by experiment, that the velocity with which an electric disturbance travels along a straight or slightly flexed metal wire is equal to the velocity of light.

If, however, the wire is closely coiled into a helix we have to treat the helix as if it were a linear conductor, and the velocity of the wave along it is inversely as the square root of the product of the capacity and inductance of the helix per unit of length.

7. Oscillations in an Earthed Aerial Wire.—A case of great practical importance arises when we consider the oscillations set up in a metal rod, like a lightning conductor, one end of which is in good connection with the earth and the rest of the wire is free, insulated and placed more or less vertically in the air. This wire is called an *aerial wire*, or *antenna*, or *Marconi aerial*, and is the essential element in telegraphy by electric waves on the Marconi system.

There are three ways in which we may set up the oscillations in this wire.

I. The wire may be cut at a point near the earth and two spark balls placed at this point. The secondary terminals of an induction coil are then attached to these balls. When the coil is in action the upper part of the wire is charged to a high potential and then discharged across the air gap. Just before discharge the upper portion of the wire has a certain capacity with regard to the earth and takes a certain charge. This discharge takes place across the spark gap, and as the spark has a low resistance the discharge is oscillatory, but greatly damped by reason of the rapid radiation of the energy.

The condition when the spark is passing is that the lower end of the aerial near the earth is at zero potential, or there is a potential node at this place. Since, however, there must be a current node at the upper end of the wire there must be an antinode of potential there.

It is easily seen, therefore, without more calculation, in the light of explanations already given, that the fundamental electrical oscillation which can be excited on the wire is one in which the amplitude of the potential increases all the way up the wire from the earth end to the summit.

The first harmonic oscillation which can be excited is one having three times the frequency of the fundamental, and it has a node about

one-third of the length of the aerial from the top. We may represent the amplitude of the potential variation by the ordinate of a dotted line and the aerial itself by a firm line. In Fig. 19 the thick black vertical lines represent the earthed aerial wire, and the two small circles the spark balls, the lower one being connected to an earth plate, E. The horizontal distance of the dotted line from the firm line represents in diagrammatic form the potential variation up the aerial. If the oscillation is the fundamental oscillation, then the potential increases all the way up the aerial from the spark balls to the top. If the electric oscillation is the first harmonic, there is one potential node about one-third of the way from the top. If the oscillation is the

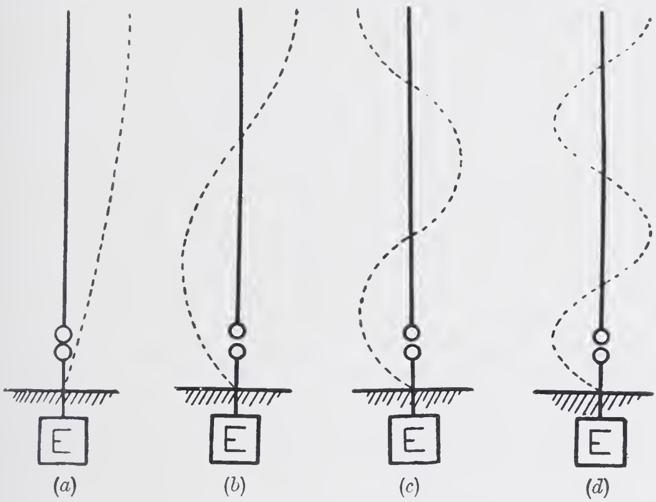


FIG. 19.—Diagram representing the Fundamental (*a*) and Harmonic (*b*), (*c*), (*d*) Oscillations of Potential on a Vertical Earthed Antenna.

second harmonic, there are two potential nodes and $2\frac{1}{2}$ semi-waves of potential on the wire. Thus we have the distribution of potential, as follows:—

Oscillation taking place on the aerial.	Number of potential nodes not including the one at earth.	Number of quarter waves of potential on the aerial.
Fundamental	0	1
1st harmonic	1	3
2nd ,, ...	2	5
3rd ,, ...	3	7
*n*th ,, ...	*n*	$(2n+1)$

The above distributions are represented in Fig. 19. The distribution of current in the aerial is such that antinodes of current occur at the same places where nodes of potential exist, and *vice versâ*.

Thus at the summit of the aerial, then, is a node of current or no current and an antinode of potential or a maximum potential

variation. At the base or earthed end there is a node of potential or no potential, but an antinode of current or a maximum value of the current. Electric current is, so to speak, pumped into and sucked out of the earth when the aerial is in oscillation. If there exist harmonic oscillations, then the current at different points in the aerial is not flowing in the same direction at the same time, but at two adjacent points may be moving in opposite directions.

Analytically, we may arrive at the above result as follows: Referring to equations (9) and (10), § 2 of this chapter, we have the expressions for the potential and current at any point in the wire having abscissa equal to x when traversed by electrical oscillations. Let us suppose that R and K are negligible in value compared with pL and pC, then we have—

$$V = a\epsilon^{+j\beta x} + b\epsilon^{-j\beta x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (68)$$

$$I = \sqrt{\frac{C}{L}}(a\epsilon^{+j\beta x} - b\epsilon^{-j\beta x}) \quad . \quad . \quad . \quad . \quad (69)$$

If $x = 0$, as at the lower end of the aerial, then $V = 0$. Hence $b = -a$, and therefore—

$$I = \sqrt{\frac{C}{L}}a(\epsilon^{+j\beta x} + \epsilon^{-j\beta x}) \quad . \quad . \quad . \quad . \quad (70)$$

$$= 2a\sqrt{\frac{C}{L}}\cos \beta x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

If, then, $x = l$, as at the upper end of the aerial, we have $I = 0$, and therefore $\cos \beta l = 0$.

Therefore, also, we must have $\beta l = \frac{m\pi}{2}$, where m is some odd integer.

But $\beta = \frac{2\pi}{\lambda}$, where λ is the wave length of the potential wave on the aerial. Accordingly, $\lambda = \frac{4l}{m}$, and the wave lengths possible on the aerial are—

$$= 4l, \quad \lambda_1 = \tfrac{4}{3}l, \quad \lambda_2 = \tfrac{4}{5}l, \text{ etc.} \quad . \quad . \quad . \quad . \quad (72)$$

Therefore the fundamental wave length is four times the length of the aerial, and the higher harmonic oscillations have wave lengths $\frac{1}{3}$, $\frac{1}{5}$, $\frac{1}{7}$, etc., of the fundamental. If this simple theory held good, an aerial 100 feet high should radiate electric waves having a wave length of 400 feet when the fundamental oscillations are set up on it, and waves of length 133 feet, 80 feet, 59 feet, etc., corresponding to the higher harmonic oscillations. Experiment, however, shows that the ratio $\frac{\lambda}{4l}$ is only unity for a single long very thin antenna wire, but that for a thicker wire or multiple wire the ratio $\frac{\lambda}{4l}$ is always somewhat greater than unity, and may perhaps reach 1·25. According to the theory of stationary oscillations developed by Mr. H. M. Macdonald, the fundamental wave length on the aerial should be 500 feet in length, or the quarter wave length is 25 per cent. longer

than the aerial. Also the wave length of the first harmonic, instead of being equal to $\frac{4l}{3}$, is equal to $\frac{7l}{5}$ according to Macdonald's theory, and the wave length of the second harmonic is $\frac{4l}{5}$ by both the simple and more complete theories. The value of the wave length tending to become equal to $\frac{4l}{(2m+1)}$ for the mth harmonic.[18]

II. The wire may have the oscillations induced in it by an oscillation transformer.

In this case an air core transformer consisting of two interlinked circuits has one circuit inserted in the aerial wire near the base between the aerial and the earth (see Fig. 20), and the other circuit has a condenser and spark balls included in it. When oscillations are set up in the condenser circuit they induce others in the aerial circuit, and the two circuits, open and closed, may be brought into resonance with each other. This is called the *inductive coupling* of the aerial with an exciting circuit.

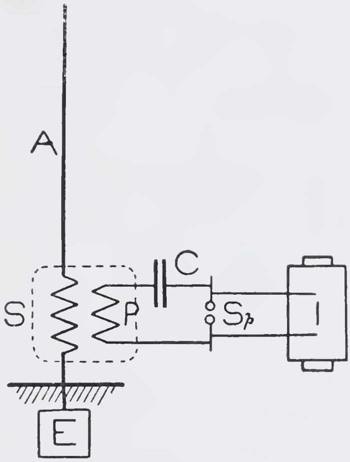


FIG. 20.—Inductively Coupled Antenna and Condenser Circuit. I, induction coil; Sp, spark balls; C, condenser; P, primary coil of oscillation transformer; S, secondary coil; A, antenna.

The electric oscillations must then be such that at the earthed end of the oscillation transformer circuit in series with the aerial we have a potential node, and at the summit of the aerial an antinode or maximum of potential.

If there is no other potential node the aerial has established on it its fundamental oscillation. The practical difficulty is to ascertain the equivalent length of the transformer secondary circuit in terms of the length of the aerial. If, for instance, the vertical aerial wire itself is 180 feet in height, and the oscillation transformer connected to it consists of a coil having a primary circuit of one turn of 4 feet in total length in circuit with the condenser and spark gap, and a secondary of ten turns of 40 feet in total length in series with the aerial wire, we require to know the length of the wave of the fundamental oscillation of such a complex aerial wire.

We cannot answer this question unless we can ascertain what length of simple straight aerial wire earthed at the bottom would have the same natural period of oscillation as the aerial with oscillation transformer inserted in it. In the above case experiment shows that the fundamental wave length of the complex aerial is very nearly equal to that of a simple aerial having a total length equal to the

[18] See H. M. Macdonald, "Electric Waves," Adams Prize Essay, 1902, p. 112.

joint lengths of the actual aerial (180 feet) and twice the length of the circuit of the oscillation transformer (40 feet) in series with it, viz. to a simple aerial having a length of $(180 + 2 + 40) = 260$ feet. The general problem is, however, very intractable, as we cannot define sufficiently accurately the conditions. We may, however, regard the arrangement in its simplest form as consisting of a piece of straight wire attached to the end of a short coil of wire in which is created a periodic electromotive force. If the coil is very short, the turns very open, the velocity of the potential wave along the coil will not be very different from its velocity along the straight wire. If, however, the turns of the oscillation circuit lie close together, its inductance is greater than that of the same wire stretched out straight, the velocity of the wave along it is less than along an equal length of straight wire of the same kind, and the oscillation circuit counts for more than its actual length in feet when added to the actual aerial. Thus, for instance, if the oscillation circuit consists of a wire 40 feet in length closely coiled and placed at the base of an aerial 180 feet in length, we cannot consider that the equivalent length of the aerial is $220 = (180 + 40)$ feet, but it will be something greater. Also the true fundamental wave length of the aerial will be more than four times 220 feet. Generally, if a simple aerial wire having a length l is attached to the secondary circuit of an oscillation transformer having a total length of secondary circuit l', the lower end of this last circuit being earthed, then we may consider it to be equivalent to a simple aerial wire of length $Ml' + l$, where M is some multiplier depending on the form of the oscillation transformer.

One type of oscillation transformer used in wireless telegraphy, devised by Marconi, consists of a wooden frame, on which the primary and secondary circuits are wound. The secondary circuit may consist of, say, 10 turns of wire, each turn being 4 feet in length. If, then, such an oscillation transformer has its secondary circuit connected on between an aerial 180 feet high and the earth, and its primary circuit contains a spark gap and a suitable condenser, these two circuits can be "tuned" or syntonized. We have, then, to consider the aerial wire of 180 feet in length joined to a circuit of an oscillation transformer 40 feet in length, and the question arises, What is the length of the wave of the fundamental oscillation of such a compound wire circuit? From some experiments by the author it appears that the factor M above mentioned may be a number near to 2 or 3 for an oscillation transformer of the type just described. Hence the equivalent length of simple aerial would be about $180 + (2 \times 40)$ feet $= 260$ feet. The length of the fundamental wave is, then, nearly five times 260 feet, or 1300 feet. The length of the first harmonic wave λ_1 is such that $\frac{\lambda_1}{2} + \frac{\lambda_1}{5}$ must be equal to 260, or $\lambda_1 = 370$ feet.

The length of the second harmonic wave λ_2 must be such that $\lambda_2 + \frac{\lambda_2}{5} = \frac{6}{5}\lambda_2$ is equal to 260 feet, or $\lambda_2 = 216$ feet, and the length of the mth harmonic wave λ_m is such that—

$$m\frac{\lambda_m}{2} + \frac{\lambda_m}{5} = l + Ml' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (73)$$

where l is the length of the aerial wire, and l' is the total length of the secondary circuit of the oscillation transformer in series with the aerial, and M is the factor for the oscillation transformer used.

Practical measurements made with the author's cymometer or wave-measuring instrument confirm the above statements.

Thus, for instance, an aerial wire 70 feet in length was set up at University College, London. Of this length 50 feet was vertical and outside a building, and 20 feet was nearly horizontal and inside the building. Using this wire with a pair of spark balls inserted between the lower end and the earth, as a simple aerial, fundamental oscillations were set up in it, and their frequency and corresponding wave length measured with the Fleming Cymometer.[19] The fundamental wave length was found to be 360 feet. This is very nearly equal to five times the total length of the aerial, or to 5×70. It was certainly much more than four times the length of the total aerial. The aerial was then joined at the base to the secondary circuit of an oscillation transformer. This secondary circuit consisted of 10 turns of wire, having a total length of 60 feet wound on a square wooden frame.

Oscillations were induced in this secondary circuit by others set up in the primary circuit of one turn, which was in series with a spark gap and condenser.

The wave now radiated from the aerial was found to have a wave length of about 960 or 970 feet. We see that $70 + 2 \times 60 = 190$. Hence the equivalent simple aerial would have a length of 190 feet, and $5 \times 190 = 950$. Hence the radiated fundamental principal wave has a wave length of five times the length of the equivalent simple aerial.

Another confirmatory experiment was made with another aerial 180 feet in height, joined to earth through the secondary circuit of an oscillation transformer, this circuit consisting of ten turns of wire having a total length of 40 feet. Hence the equivalent length of simple aerial should be $180 + 2 \times 40 = 260$.

The first harmonic oscillation was excited on this aerial, and found to radiate a wave 370 feet in length. By the above theory, if we call λ_1 this first harmonic wave length, we should have—

$$\frac{\lambda_1}{2} + \frac{\lambda_1}{5} = 180 + 2 \times 40 = 260 \text{ feet}$$

$$\text{or} \quad \lambda_1 = 371 \text{ feet}$$

and a value 370 feet was found by experiment. The fundamental wave in this case would have a length of $5 \times 260 = 1300$ feet.

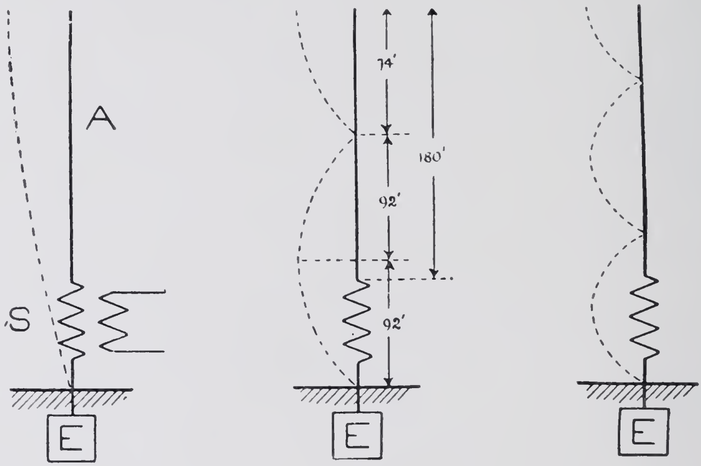
The distribution of potential in such an aerial would then be as represented in the diagram in Fig. 21.

Let A be the aerial wire supposed to be 180 feet in height, and S the secondary circuit of the oscillation transformer in series with it, and E the earth plate. Then, when the fundamental electric oscillation is excited on the aerial, the summit of the aerial is an antinode of potential and the base a node, and the potential amplitude increases

[19] For description of this cymometer and instructions for using it, see Chap. VI. of this treatise.

all the way up the aerial, as indicated by the ordinates of the dotted curve (see (*a*), Fig. 21). When the first harmonic oscillation is excited there is a node of potential about halfway between the summit of the aerial and the upper terminal of the oscillation transformer.

In the case considered we have an aerial 180 feet in height, joined on to an oscillation transformer having a secondary circuit 40 feet in length, with a length factor (M) for that circuit equal to 2. The necessary conditions are fulfilled if we have a node of potential 74 feet below the top of the aerial. There is, therefore, an antinode or loop of potential just above the upper terminal of the oscillation transformer circuit (see (*b*), Fig. 21). When the second harmonic oscillation is



(*a*) (*b*) (*c*)

FIG. 21.—Fundamental and Harmonic Oscillations of Potential excited on an Inductively Coupled Antenna.

excited there are two nodes of potential on this aerial, one 43 feet and the other 151 feet below the top of the aerial (see (*c*), Fig. 21).

An experimental examination of the relation of the lengths of wave emitted by a plain antenna to its length has been made by M. Ferrié (see M. C. Tissot, "Étude de la Résonance des Systèmes d'Antennes dans la Telegraphie sans fils." Gauthier-Villars. Paris, 1906).[20]

M. Ferrié has given some measurements taken for different antennæ. Thus, for instance, for single wires, 20 to 30 metres in length, the ratio of $\frac{\lambda}{4h}$, where λ is the wave length and h the antenna length, is always rather less than unity. For branched antennæ it is greater than unity, 1·03 to 1·16 or more. The ratio increases with the number of branches and with their separation. It may amount to 1·27 or 1·3 for a many-branched antenna.

For a single antenna the above ratio tends to unity as the diameter of the wire decreases.

[20] See also M. Ferrié, *Comptes Rendus*, 1903, p. 128; or *Jour. Soc. Franc., Phys.*, April 8, 1904.

If the antenna is inductively excited and has the secondary circuit of an oscillation transformer inserted in it, then the ratio of $\frac{\lambda}{4h}$ may be much greater than unity, rising to a value of 1·7 or even 2.

M. Tissot (*loc. cit.*) points out that the decrement or damping of the oscillations in an antenna in which they are excited by a spark discharge increases with the increase in the ratio of $\frac{\lambda}{4h}$. Hence, not only is the above fraction larger for a branched than for a single wire antenna, but the damping or radiation decrement of the branched antenna is larger than for the single wire antenna, both being excited in the same manner by charge and discharge across a spark gap.

8. Stationary Oscillations on Closed Oscillatory Circuits.—If a length of wire, whether a single wire or a helix or coil, has its ends attached to two metal plates which are in contiguity to each other but separated by a dielectric, we have an oscillatory circuit possessing inductance and capacity. If these metal plates are very near to each

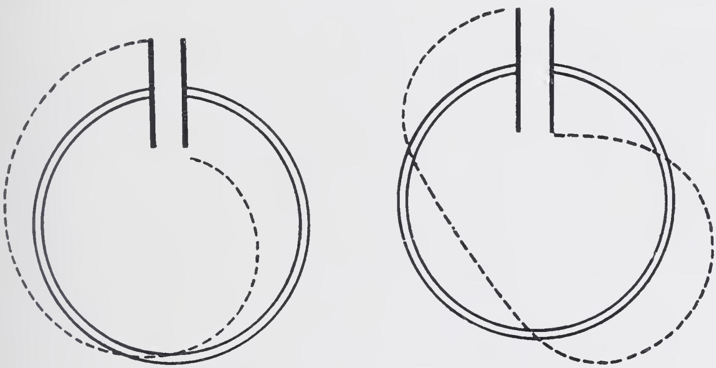


FIG. 22. FIG. 23.

other the circuit is generally called a *closed* oscillatory circuit. If, on the other hand, they are widely separated it is called a more or less *open* oscillatory circuit. The distinction between these circuits is a matter of degree, but we shall show in the next chapter that the open circuit has superior powers of creating electromagnetic radiation when it is the seat of high frequency oscillations. The closed circuit can, however, have stationary oscillations excited in it either on fundamental or higher harmonics.

The conditions which must be observed are that the plates of the condenser at any instant carry charges of opposite sizes and hence are respectively above and below the zero of potential. Accordingly, it will be seen that the fundamental oscillation necessitates one node of potential, and if we represent the distribution of the amplitude of potential by the distance of a dotted line from the line representing the circuit we can indicate the fundamental oscillation of a closed circular circuit as on the diagram in Fig. 22.

There is one potential node at the symmetrical point, and at this place therefore a current antinode or loop. Through the condenser

there is no conductive current, and therefore we may say that the condenser is a node of current. To excite the first harmonic oscillation we must then have three nodes of potential and the plates of the condenser at opposite potentials, as in Fig. 23. The second harmonic involves five nodes of potential, and the third harmonic seven nodes, and so on. If the circuit consists of a single wire bent into a circle or square, these nodes will then be symmetrically situated; but if the circuit has loops or coils of wire in it, then these will bestow upon it unequal inductance per unit of length, and this will cause a displacement of the position of the nodes.

Generally speaking any sudden change in the inductance or capacity of a circuit at a certain point causes a reflection of a wave of potential travelling along it, and if the distance between such places of reflection is rightly adjusted in reference to the velocity of the wave, the result is to set up stationary oscillations on the wire. In the case of a single wire the velocity of propagation of a wave along it is the same as that of light, viz. 3×10^{10} cms. per second. In the case of spirals of wire or other coiled circuits, the velocity of the wave of potential along the helix is generally much less, that is when we reckon the distance as distance along the helix and not along the wire. The wave velocity is then determined by the inductance and capacity of the circuit per unit length.

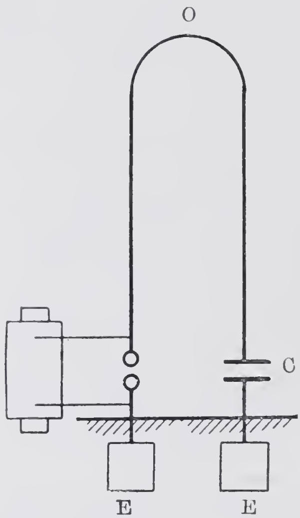


FIG. 24.—Looped Antenna.

A particular case of oscillations in a closed circuit are those which can be set up in a loop antenna with both ends earthed. Let a loop of wire be formed by erecting two insulated vertical wires parallel to each other and joining them together at the top. In one branch let a condenser be inserted and in the other a pair of spark balls, the lower ball and lower condenser plate being connected to earth plates, E, as shown in Fig. 24. Then when the condenser is charged and discharged we have oscillations set up in the loop circuit. If this circuit has a total length which is large, or comparable with the proper wave length corresponding to the capacity and inductance, we may have stationary oscillations set up on the loop. The current may not be in the same direction at all points in the loop at the same instant, and there may be nodes and antinodes of potential and current distributed along the wire. We shall investigate this effect, following a mathematical analysis which is due to Dr. G. Seibt.[21]

In the first place, let C_1 be the capacity of the condenser and C

[21] See Thesis for the Doctorate, presented to the University of Rostock by Dr. Georg Seibt, entitled "Electrische Drahtwellen," Berlin, 1902, p. 27; or *Elektrtechnische Zeitschrift*, vol. xxiii., April 10, 17, 24, May 1, 8, 1902.

the capacity per unit of length of the loop or aerial wire. And let L be the inductance per unit of length of this wire. Then, if V is the potential at any point in the wire, and I the current considered as vector quantities, we have the value of these given by the equations—

$$V = a\epsilon^{+Px} + b\epsilon^{-Px} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (74)$$

$$I = \frac{P}{R + jpL}(a\epsilon^{+Px} - b\epsilon^{-Px}) \quad . \quad . \quad . \quad . \quad (75)$$

as shown in § 1 of this chapter.

If we assume, as we may do, that the resistance and insulation conductance of the wire are negligible, then these equations take the form—

$$V = a\epsilon^{j\beta x} + b\epsilon^{-j\beta x} \quad . \quad . \quad . \quad . \quad . \quad . \quad (76)$$

$$I = \sqrt{\frac{C}{L}}(a\epsilon^{j\beta x} - b\epsilon^{-j\beta x}) \quad . \quad . \quad . \quad . \quad (77)$$

Let us suppose the earth connections removed, the lower spark ball being connected directly to the lower condenser plate. Take the symmetrical point O at the upper end of the loop (see Fig. 24) as origin, and measure x from it. Then when $x = 0$ we have $V = 0$, because the point O is symmetrically situated. Hence, then, $a + b = 0$, or $b = -a$.

Let the length of the loop forming the aerial be l. Then when $x = \frac{l}{2}$ we have the value of the potential at the condenser terminal, or—

$$V = a\left(\epsilon^{j\beta xl/2} - \epsilon^{-j\beta l/2}\right) \quad . \quad . \quad . \quad . \quad . \quad (78)$$

Therefore at this point the current into the condenser must be given by the equation—

$$I = \sqrt{\frac{C}{L}}a\left(\epsilon^{j\beta l/2} + \epsilon^{-j\beta l/2}\right) \quad . \quad . \quad . \quad (79)$$

But since the potential difference of the condenser plates is 2V, and since the current into the condenser is equal to $C_1\frac{d(2V)}{dt}$, and is 90° in advance of this potential difference in phase, we must have the current in vector notation given by—

$$I = -j2VC_1p \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (80)$$

Hence, equating the two expressions for the current, we have—

$$a\sqrt{\frac{C}{L}}\left(\epsilon^{j\beta l/2} + \epsilon^{-j\beta l/2}\right) = -2jpC_1a\left(\epsilon^{j\beta l/2} - \epsilon^{-j\beta l/2}\right)$$

$$\text{or} \quad \sqrt{\frac{C}{L}}\cdot\frac{1}{2pC_1} = \tan\beta\frac{l}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (81)$$

Bearing in mind that $\beta = p\sqrt{\mathrm{CL}}$, we can easily show that the above equation transforms into—

$$\left(\frac{\pi}{T}l\sqrt{\mathrm{CL}}\right)\tan\left(\frac{\pi}{T}l\sqrt{\mathrm{CL}}\right) = \frac{\mathrm{C}l}{4\mathrm{C}_1} \quad . \quad . \quad . \quad . \quad . \quad (82)$$

Since $\mathrm{C}l$, viz. the capacity of the whole aerial, is generally very small compared with the capacity of the condenser C_1, the above equation is equivalent to—

$$\theta \tan \theta = 0 \text{ (nearly)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (83)$$

We may therefore write θ^2 instead of $\theta \tan \theta$. Hence we have—

$$\frac{\pi^2}{T^2}l^2\mathrm{CL} = \frac{\mathrm{C}l}{4\mathrm{C}_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (84)$$

$$\text{or} \quad T = 2\pi\sqrt{\mathrm{C}_1\mathrm{L}l} \quad . \quad . \quad . \quad . \quad . \quad (85)$$

This, however, is the usual expression for the time period of a circuit consisting of a capacity C_1 in series with an inductance $\mathrm{L}l$.

Hence one possible mode of oscillation is the fundamental mode in which the current oscillates at each discharge, but is in the same direction in all parts of the loop at the same time.

The periodic time of the harmonics is obtained by finding the solutions of the equation—

$$\tan\left(\frac{\pi}{T}l\sqrt{\mathrm{CL}}\right) = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (86)$$

These are—

$$\frac{\pi}{T}l\sqrt{\mathrm{CL}} = \pi, \quad 2\pi, \quad 3\pi \ldots n\pi \quad . \quad . \quad . \quad (87)$$

Therefore—

$$T_1 = l\sqrt{\mathrm{CL}}, \quad T_2 = \frac{l}{2}\sqrt{\mathrm{CL}}, \quad T_3 = \frac{l}{3}\sqrt{\mathrm{CL}}, \text{ etc.} \quad (88)$$

give the periodic times of the harmonic oscillations, and the corresponding wave lengths are—

$$\lambda_1 = l, \qquad \lambda_2 = \frac{l}{2}, \qquad \lambda_3 = \frac{l}{3} \quad . \quad . \quad . \quad . \quad (89)$$

In all cases, therefore, there is a potential node or current antinode at the summit of the loop at the symmetrical point. At corresponding points at the same level on the two sides of the loop the current in one side of the loop is in the opposite direction at any one moment to the current in the other side of the loop. Hence there can be no radiation from the loop as a whole.

On the other hand, the condition of things is altered if the lower condenser plate is connected to earth.

To investigate the conditions which then arise, we measure the distances x from the earthed plate of the condenser. Then, as before,

let the length of the loop be l and let V and I be the potential and current at any point. We have—

$$V = a\epsilon^{j\beta x} + b\epsilon^{-j\beta x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (90)$$

$$I = \sqrt{\frac{C}{L}}\left(a\epsilon^{j\beta x} - b\epsilon^{-j\beta x}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (91)$$

In the first equation put $x = 0$, then $a = -b$. Also, if we put $x = l$, we have the current I' flowing into the condenser.

Making these substitutions, we have—

$$I' = a\sqrt{\frac{C}{L}}\left(\epsilon^{j\beta l} + \epsilon^{-j\beta l}\right) \quad . \quad . \quad . \quad . \quad . \quad (92)$$

But the value of I' is also given by the equation—

$$I' = -jpC_1V'$$

Hence, equating these values of I' and inserting the proper value of V′, we can easily find that—

$$\sqrt{\frac{C}{L}} \cos \beta l = pC_1 \sin \beta l \quad . \quad . \quad . \quad (93)$$

$$\text{or} \quad \sqrt{\frac{C}{L}} \cdot \frac{1}{C_1} = p \tan pl\sqrt{CL} \quad . \quad (94)$$

$$\text{or} \quad \left(\frac{2\pi}{T}l\sqrt{CL}\right) \tan \left(\frac{2\pi}{T}l\sqrt{CL}\right) = \frac{Cl}{C_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (95)$$

Hence, as before, the time period of the fundamental oscillation is obtained from the equation—

$$\left(\frac{2\pi}{T}l\sqrt{CL}\right)^2 = \frac{Cl}{C_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (96)$$

$$\text{or} \quad T = 2\pi\sqrt{C_1Ll} \quad . \quad . \quad . \quad . \quad . \quad . \quad (97)$$

Since $\frac{Cl}{C_1}$ is nearly zero, the time periods of the harmonics are given by the solution of the equation—

$$\tan \left(\frac{2\pi}{T}l\sqrt{CL}\right) = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (98)$$

$$\text{or} \quad \frac{2\pi}{T}l\sqrt{CL} = \pi, \quad 2\pi, \quad 3\pi, \text{ etc.} \quad . \quad . \quad . \quad (99)$$

Accordingly, the time periods are given by—

$$\left.\begin{array}{lllll} & T = l\sqrt{CL}, & \frac{1}{2}l\sqrt{CL}, & \frac{1}{3}l\sqrt{CL}, \text{ etc.} \\ \text{or} & T = 2l\sqrt{CL}, & \frac{2}{3}l\sqrt{CL}, & \frac{2}{5}l\sqrt{CL}, \text{ etc.} \end{array}\right\} \quad . \quad (100)$$

and the respective wave lengths possible by the equations—

$$\left.\begin{array}{llll} & \lambda = l, & \frac{l}{2}, & \frac{l}{3}, \text{ etc.} \\ \text{or} & \lambda = 2l, & \frac{2}{3}l, & \frac{2}{5}l, \text{ etc.} \end{array}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (101)$$

It is clear, therefore, that two sets of harmonics can arise.

First, a set which have wave lengths given by $\lambda = l, \frac{l}{2}, \frac{l}{3}$, etc. These have a potential node and a current antinode at the symmetrical or middle point of the loop, and, as already explained, these are badly radiated.

Secondly, there may arise another set which have wave lengths given by—

$$\lambda = 2l, \quad \frac{2l}{3}, \quad \frac{2l}{5}, \text{ etc.,}$$

and for these oscillations the middle point in the loop is a current node or potential antinode, and, moreover, at the same level in the two sides of the loop the currents are moving in the same direction. The two sides of the loop therefore act like two separate parallel and adjacent Marconi aerials connected together at the top, and the closed loop radiates. The first set of harmonics which includes the fundamental is non-radiative, and for these the whole length of the loop is an integer multiple of the wave length of the harmonic.

The second set of harmonics is well radiated, and for these the whole length of the loop is an odd integer multiple of half the wave length. For in these the current at corresponding points in the two vertical sides of the loop is in the same direction.

These looped earthed aerials are therefore a curious instance of a circuit which can be more radiative for some frequencies than for others.

These well radiated harmonics are therefore damped out by radiation more quickly than the badly radiated ones. The reader is referred to an interesting paper by Mr. James E. Ives, in the *Physical Review* for February, 1910, vol. 30, for a discussion of the wave length and overtones of a linear electrical oscillator; and further reference is made to this matter in Chap. VIII., § 8, of this book.

CHAPTER V

ELECTROMAGNETIC WAVES

1. The Electromagnetic Medium and its Properties.—The fact that electric oscillations produced in one circuit can set up secondary oscillations in another circuit at a distance forces upon us the consideration of the nature of the machinery by which this is effected.

Notable investigators of natural phenomena, from Newton to Maxwell, have strongly expressed their conviction that actions of this character make it necessary for us to postulate some interconnecting medium, or else we have to take refuge in the bare assumption, repugnant alike to common sense as well as philosophic thought, that physical effects can be produced at a distance without the aid of any intervening mechanism. In his well-known second letter to Bentley, Newton, writing on the attraction of matter, said

> "that gravity should be innate and essential to matter, so that one body can act upon another at a distance through a vacuum without the mediation of anything else by which their action may be conveyed from one to another, is to me so great an absurdity that I believe no man who has a competent faculty of thinking in physical matters can ever fall into it."

The propagation of light with a finite velocity through interstellar space has compelled us to accept the hypothesis, with some considerable body of arguments in its favour, that space is occupied by a medium called the æther, capable of transmitting undulations, which, when falling on the retina of the eye, produce the sensation of light. Ampère, Faraday, Henry, and others, moreover, long ago arrived at the conclusion that electric and magnetic phenomena, especially the facts of electric and magnetic induction, demanded also the assumption of a special medium for their explanation. Maxwell has remarked that it is clearly unphilosophical to postulate more than one æther. Hence the work done by Huyghens, Arago, Fresnel and their followers in consistently deducing observed optical effects from the assumed properties of the luminous æther called for a corresponding definite effort on the part of electricians. The work began when Clerk Maxwell took up the study of Faraday's experimental researches, and endeavoured to discern whether the ideas of Faraday, which were then not in accord with current views, were capable of being translated into mathematical language, and made the foundation of a new method of regarding electrical facts.

The publication in 1865 of James Clerk Maxwell's paper, "A Dynamical Theory of the Electromagnetic Field," marks a great epoch

in the history of scientific thought.[1] In that paper Maxwell applied to the facts of electromagnetism certain equations and methods of analysis which the French mathematician, Joseph Louis Lagrange, had employed in formulating the dynamical relations of the kinetic and potential energies, the velocities and momenta of various parts of any system of interconnected moving material masses. Maxwell saw that in electric and magnetic actions we have energy involved, and that this energy takes two forms, electrostatic and electrokinetic, which have a close similarity to energy of strain and motion. Moreover, the interconvertibility of various forms of energy, and the fact that we can invaluate them in their equivalent in motional energy, whilst indicating that all energy is probably in the ultimate issue kinetic in nature, affords at the same time logical ground for applying the methods of Lagrange to the phenomena of electricity and magnetism.

The systematic examination that has been made of the relations of the electric and magnetic quantities shows us that we can co-ordinate them in a scheme of related magnitudes, each one corresponding to some well-known dynamical equivalent. Thus, corresponding to the fundamental dynamical quantities, *e.g.* mass, velocity, acceleration, momentum, force, energy, and activity or power, we can place in contiguity such electrical quantities as inductance, current, rate of current change, total magnetic flux, electromotive force of self-induction, current energy, and rate of dissipation of current energy. In parallel with mechanical quantities such as stress, strain, elastic yielding, strain energy, we can place analogous electric and magnetic quantities such as electric and magnetic forces, displacement or magnetic flux, dielectric constant or magnetic permeability, and electric or magnetic energy.

We may, as Heaviside and other writers have shown, draw up many consistent schemes of analogy between mechanical and electromagnetic quantities, but we must beware of enslaving ourselves to any one particular set of mechanical similarities. Analogies of this kind are often like mountain paths, which begin in well-beaten routes, but sooner or later, if followed up too far, terminate in a barren region. There remains, however, the fact that corresponding to two well-recognized forms of mechanical energy, namely, motional energy measured by half the product of momentum and velocity, and configurational energy measured by half the product of stress and strain, we have a duplex system of electric and magnetic quantities which are for the most part circuital or manifested in circuits. Thus we have *two circuits*, the electric and magnetic; *two physical effects* produced in these, *electric strain* or *displacement* (D) and *magnetic flux* (F); *two agencies* producing these effects, the electric and magnetic forces; *two specific physical qualities* of the circuits corresponding thereto, namely, *dielectric constant* and *magnetic permeability*, or, as Mr. Oliver Heaviside calls them, *permittivity inductivity*; also *two line integrals* of electric and magnetic force called respectively *voltage* (V) and *gaussage* (G); *two forms of energy*, electric and magnetic; and *two* corresponding *forms of activity* or power.

[1] Maxwell sent this paper to the Royal Society on October 12, 1864. It was read on December 8, 1864, and printed in the *Philosophical Transactions of the Royal Society* for 1865, vol. 155, p. 419.

Moreover, we have a curious interlinking of these quantities when circuital, best expressed by *two circuital laws* which symbolically and in rational units are stated as follows [2]:—

$$-\dot{\mathrm{F}} = \mathrm{V} \text{ and } \dot{\mathrm{D}} = \mathrm{G},$$

where the *dot* over the symbol signifies time differentiation, or $\frac{d}{dt}$.

The first of these equations is merely the symbolical expression of Faraday's law, that the electromotive force or line integral of electric force round any circuit is numerically equal to the time rate of decrease of the magnetic flux through it $(-\dot{\mathrm{F}})$; and the second is the simplest expression of Maxwell's principle that the time rate of change of electrical displacement $(\dot{\mathrm{D}})$ through any circuit is measured by the gaussage or line integral of magnetic force round the circuit.

In cases when the circuits are formed of certain kinds of matter we have also to introduce two other conceptions, namely, *electric current* and *magnetization*, which are produced when the two circuits possess *conductivity* or *susceptibility*, and when these qualities are present the fundamental equations take a more general form, which, expressed by Heaviside in rational units, are—

$$-(\dot{\mathrm{F}} + \dot{\mathrm{M}}) = \mathrm{V} \text{ and } \dot{\mathrm{Q}} + \dot{\mathrm{D}} = \mathrm{G},$$

where M stands for magnetization, and Q for a quantity of electricity moved non-elastically past any section of the circuit.[3]

Out of this double-stranded system of interlinked quantities and their fundamental relations, it follows that in considering the measurement of any one electric or magnetic quantity we can arrive at the same point by two paths, starting either from an electric or magnetic definition. Thus, we may consider an electric current to be due to a series of successive discharges of electric strain by a conductor, or we may consider it to arise from the movement of a magnet to or from a closed conducting circuit. In the one case our measure of current involves the quantity K or the dielectric constant of the medium in which the electric strain takes place. In the other case it involves μ, or the magnetic permeability of the medium which encloses the magnet and the circuit.

In every case in which this double measurement of the same quantity can be carried out, the numerical ratio of the two measurements when conducted in absolute or dynamical units gives us a number which it can be shown represents either the geometrical mean of K and μ, viz. $\sqrt{\mu\mathrm{K}}$, or its reciprocal $\frac{1}{\sqrt{\mu\mathrm{K}}}$, or their squares $\mu\mathrm{K}$ and $\frac{1}{\mu\mathrm{K}}$. In other words, it gives us a numerical value for the

[2] For a fuller information of Mr. Heaviside's system of rational electric and magnetic units, the reader must be referred to his book, "Electromagnetic Theory," vol. i. chap. ii.

[3] The systematic formulation of these circuital laws, as well as a fuller appreciation and elucidation of Maxwell's views, have been assisted of late years in a remarkable degree by the writings of Mr. Oliver Heaviside.

product of these two qualities, but it does not tell us their individual values for any medium.[4]

An immense number of investigations of the last twenty years have shown that the product μK in the centimetre-gramme-second system of absolute units for air or a good vacuum closely approximates to a value $\frac{1}{9 \times 10^{20}}$, and is identical numerically with the square of the reciprocal of the velocity of light. This numeric 3×10^{10} will be hereafter denoted by the symbol u. A list of some of the principal determinations of this unitary ratio called u, obtained prior to 1897, is given in Table I.

A résumé of all determinations of the value of u previous to 1900 was prepared by H. Abraham for the International Congress of Physics which met at Paris in that year (see *Congrès International de Physique*, 1900, *Rapports II.* p. 247). Abraham states that he considers the most accurate results to be as follows:—

Himstedt	$3 \cdot 0057 \times 10^{10}$
Rosa	$3 \cdot 0000 \times 10^{10}$
Thomson and Searle	$2 \cdot 9960 \times 10^{10}$
H. Abraham	$2 \cdot 9913 \times 10^{10}$
Pellat	$3 \cdot 0092 \times 10^{10}$
Hurmuzescu	$3 \cdot 0010 \times 10^{10}$
Perot and Fabry	$2 \cdot 9978 \times 10^{10}$
Mean value	$3 \cdot 0001 \times 10^{10}$

Abraham considers that this mean of the best results, viz. 3×10^{10}, probably does not differ from the true value by more than 1 part in 1000. The most recent result is that of E. B. Rosa and N. E. Dorsey (see *Bulletin of the Bureau of Standards*, Washington, U.S.A., May 20, 1907, vol. 3), which gave the value $2 \cdot 9963 \times 10^{10}$.

The above values are all values in air, but if expressed for vacuum require to be increased by 55 parts in 1,000,000.

A glance at the above table shows that the numerical value of u or of $\frac{1}{\sqrt{\mu K}}$ for air or vacuum is nearly identical with that of the velocity of light through empty space when measured in centimetres per second.

The best measurements of the velocity of light are those of—

Michelson (1885)	$= 2 \cdot 99853 \times 10^{10} \frac{\text{cms.}}{\text{sec.}}$
Newcomb (1883)	$= 2 \cdot 99860 \times 10^{10}$,,
Perrotin (1902)	$= 2 \cdot 99860 \times 10^{10}$,,

Weinberg, discussing the results, comes to the conclusion that the most probable value of the velocity of light in vacuo is $2 \cdot 99852 \times 10^{10} \frac{\text{cms.}}{\text{sec.}}$ with an accuracy of 1 part in 10,000.

Hence we may say that the unitary ratio expressed in the same

[4] For a more complete discussion of this matter, the reader is referred to the author's treatise on "The Alternate Current Transformer," vol. 1, p. 354 (The Electrician Printing and Publishing Company, London).

units of length and time is identical with the velocity of light within 1 part in about 3000.

The fact that the ratio between electric and magnetic quantities measured on two systems is so closely connected with the numerical

TABLE I.

TABLE OF OBSERVED VALUES OF u IN CENTIMETRES PER SECOND.

Year.	Name.	Reference.	Electric quantity measured.	u in centimetres per second.
1856	Weber and Kohlrausch	*Electrodynamische Maasbestimmungen und Pogg. Ann.*, xcix., Aug. 10, 1856	Quantity	$3{\cdot}107 \times 10^{10}$
1867 1868	Lord Kelvin and W. F. King	"Report of British Association, 1869," p. 434; and "Reports on Electrical Standards," F. Jenkin, p. 186	Potential	$2{\cdot}81 \times 10^{10}$
1868	Clerk Maxwell	*Phil. Trans. Roy. Soc.*, 1868, p. 643	"	$2{\cdot}84 \times 10^{10}$
1872	Lord Kelvin and DugaldMcKichan	*Phil. Trans. Roy. Soc.*, 1873, p. 409	"	$2{\cdot}89 \times 10^{10}$
1878	Ayrton and Perry	*Journal of the Society of Telegraph Engineers*, vol. viii. p. 126	Capacity	$2{\cdot}94 \times 10^{10}$
1880	Lord Kelvin and Shida	*Phil. Mag.*, 1880, vol. x. p. 431	Potential	$2{\cdot}955 \times 10^{10}$
1881	Stoletow	*Soc. Franc. de Phys.*, 1881	Capacity	$2{\cdot}99 \times 10^{10}$
1882	F. Exner	*Wien. Ber.*, 1882	Potential	$2{\cdot}92 \times 10^{10}$
1883	J. J. Thomson	*Phil. Trans. Roy. Soc.*, 1883, p. 707	Capacity	$2{\cdot}963 \times 10^{10}$
1884	Klemencic	*Proc. of the Soc. of Telegraph Engineers*, 1887, p. 162	"	$3{\cdot}019 \times 10^{10}$
1888	Himstedt	*Electrician*, Mar. 23, 1888, vol. xx. p. 530	"	$3{\cdot}007 \times 10^{10}$
1888	Lord Kelvin, Ayrton and Perry	British Association, Bath; and *Electrician*, Sept. 28, 1888	Potential	$2{\cdot}92 \times 10^{10}$
1888	Fison	*Electrician*, vol. xxi. p. 215; and *Proc. Phys. Soc.*, London, June 9, 1888	Capacity	$2{\cdot}965 \times 10^{10}$
1889	Lord Kelvin	Royal Institution Lecture, Feb. 8, 1889	Potential	$3{\cdot}004 \times 10^{10}$
1889	Rowland	*Phil. Mag.*, 1889	Quantity	$2{\cdot}981 \times 10^{10}$
1889	E. B. Rosa	*Phil. Mag.*, 1889	Capacity	$3{\cdot}000 \times 10^{10}$
1890	J. J. Thomson and Searle	*Phil. Trans.*, 1890	"	$2{\cdot}995 \times 10^{10}$
1897	M. E. Maltby	*Wied. Ann.*, 1897	Alternating currents	$3{\cdot}015 \times 10^{10}$

value of the velocity of light, is a strong argument that there must be some common basis for optical and electromagnetic phenomena.

Since light is propagated from place to place with a finite velocity, and as the facts of interference prove it to be a wave motion, theorists had been compelled to assume the existence of a space-filling medium possessing two qualities—first, *inertia*, in virtue of which kinetic

energy is exhibited by parts of the medium in motion, and secondly an *elastic resistance* to strain or distortion of some kind, in consequence of which potential energy is stored up in the distorted medium, these two properties being the essential qualities of a medium capable of undulation.

The study of physical optics resolved itself, then, into a dynamical analysis of the phenomena, and efforts to explain them by the hypothesis of an æther possessing inertia and capable of some elastic distortion in virtue of which waves could be propagated through it.

Maxwell's electromagnetic theory starts from a more general point of view. We know nothing about the inner structure of the æther or the kind of distortions it can experience. We do, however, know that in a dielectric, even empty space, we have present at any point the two qualities permeability and dielectric constant or inductivity, and also that in electric and magnetic phenomena we are concerned with two physical effects, called respectively magnetic flux and electric displacement or strain. When these conceptions and the fundamental relations of the electric and magnetic quantities had been mathematically expressed, Maxwell found that they led to equations of the same type and form as those which express the propagation of an undulation through a continuous medium, and they indicated that if the effects we call magnetic flux or electric displacement are created at one point in space they are propagated in all directions with the velocity of light in that dielectric.

Starting from fundamental electric and magnetic facts, it has been found possible to build up a theory which embraces not only electrical but optical phenomena, and shows them to be manifestations of the properties of one single medium, modified, however, profoundly in certain localities by the presence of that which we will call gravitative matter. This comprehensive theory is generally known as Maxwell's theory, and it will be necessary to consider it at least in outline.

Broadly speaking, it may be held to be, that there exists a space-filling æther or medium, not, as far as we know, composed of gravitative matter, the principal qualities it possesses being those in virtue of which two physical states can be established in it, one called Electric Strain and other Magnetic Flux. From the known relations between these states it can be shown that when either of them is established in one place it will spread or diffuse with a velocity equal to that of light. The inference is that optical phenomena are electromagnetic in nature, and must be interpreted in terms of the known electric and magnetic properties of dielectrics, and not by the assumption of mechanical qualities which cannot be verified.

2. Maxwell's Theory of Electromagnetic Phenomena.—Since electric and magnetic forces are vector quantities having direction as well as magnitude at every point in the electric and magnetic field, and since they are obviously related to each other, we must in the first place consider some qualities of vectors generally.

Let us suppose any closed curve described in a region in which there is a distribution of a certain vector quantity, E. Divide the curve up into elements of length, ds, and at every point of the curve resolve the vector E denoting the quantity considered at that point

into components along these elements of length. Then the sum or integral of all such quantities as E cos θds, where θ is the angle between the direction of ds and the direction of the vector E at its centre, is called the *line integral of* E *along the curve.* In taking this integral, the sign of the product must be reckoned positive when the direction of the vector is in the same direction as the movement round the curve, and negative when it is against it. In many cases this line integral round a closed curve drawn in the field is zero, and the vector is then said *to have a potential.*

Thus if E denotes the electric force in the electric field near an electrified body, then $\int$E cos θds is zero for any closed curve so drawn, and the electric force is thus said to be derived from, or to have a potential.

In other cases this line integral is not zero, but has a finite value independent of the form of the path, but which is increased n times by taking the line integral n times round the circuit. This is the case with the magnetic field round a conductor conveying an electric current; for if the conductor carries a current, C, the line integral of the magnetic force taken along a line embracing the circuit can easily be shown to be equal to 4πC for a single journey round, and to $4\pi n$C for n journeys round the closed line. The vector is then said *to have a many-valued potential.*

On the other hand, the line integral may have a value which is dependent upon the form of the path. If the area enclosed by the path is small and lies in one plane, the ratio of the quotient obtained by dividing the line integral by the area of the path may have a finite limit, and in this case the limiting value is called the *curl of the vector in that plane.*

At any one point in the field there is some plane in which this ratio is a maximum, and this maximum value is generally called *the curl* of the vector.

A curl is itself a vector, and may be resolved into component curls. Very often the curl has a physical meaning with respect to the original vector which gave rise to it.

Thus it can be shown that if the vector considered is the velocity of the particles of a liquid mass at various points, then the curl denotes twice the angular velocity with which a very small sphere of the liquid, which may be supposed to enclose and coincide with the particle considered, is rotating.

Suppose we consider any vector, E, which has rectangular components, X, Y, and Z, along three rectangular axes, x, y, and z.

If, then, we describe a little rectangle on each co-ordinate plane, and take the line integral round it, we shall obtain the rectangular component of the curl. Thus on the plane of xy we have the line integral round the parallelogram $dx \,.\, dy$ with one corner at the origin given by—

$$\mathrm{X}dx + \left(\mathrm{Y} + \frac{d\mathrm{Y}}{dx}dx\right)dy - \left(\mathrm{X} + \frac{d\mathrm{X}}{dy}dy\right)dx - \mathrm{Y}dy$$

$$\text{which is equal to} \quad \left(\frac{d\mathrm{Y}}{dx} - \frac{d\mathrm{X}}{dy}\right)dx \,.\, dy$$

The above conclusion follows at once from Taylor's theorem that if y is the ordinate at any curve at abscissa x, then the ordinate corresponding to abscissa $x + dx$ is $y + \frac{dy}{dx}dx$. Hence the component curl on the plane xy is $\left(\frac{d\mathrm{Y}}{dx} - \frac{d\mathrm{X}}{dy}\right)$, and similarly the component curls in the planes yz and zx are respectively—

$$\left(\frac{d\mathrm{Z}}{dy} - \frac{d\mathrm{Y}}{dz}\right) \text{ and } \left(\frac{d\mathrm{X}}{dz} - \frac{d\mathrm{Z}}{dx}\right)$$

There is, then, a connection between a vector and its curl, the statement of which constitutes an important theorem. If we have any surface bounded by any line described in a field in which a certain vector quantity is distributed, we may cut up this surface into small elements of area. It follows by the above definition of the curl that the product of the curl for each element of area and the size of that area is equal to the line integral of the vector round the boundary of the element. Hence if we take the line integrals round all the elements, the line integral for each common boundary of any pair of elements of the area is taken twice, once negatively and once positively, and the products cancel each other. Accordingly, it is easy to see that *the line integral of a vector round the boundary of the whole of the surface is equal to the surface integral of its curl over the whole of the surface.*

Conversely, if this relation holds good between two quantities, viz. that the line integral of one is equal to the surface integral of the other, we are enabled to recognize by it that the one quantity bears to the other the relation of vector and corresponding curl.

Let us consider, then, the relation between the electric and magnetic forces and their effects, viz. the electric displacement and magnetic flux. Let E be the electric force at any point in a dielectric and H the magnetic force. Let D be the corresponding electric strain or displacement and B the magnetic flux. Then in the ordinary system of units we have—

$$\mathsf{B} = \mu\mathsf{H} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\mathsf{D} = \frac{\mathrm{K}}{4\pi}\mathsf{E} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where μ is the magnetic permeability and K is the dielectric constant.[5]

If, then, we describe any closed line in a conductor, and make the magnetic flux through it vary with time, we have produced in the circuit an electromotive force. In accordance with Faraday's law, the time rate of change of the surface integral of the magnetic flux through this area is a measure of the electromotive force created in the circuit. This electromotive force is the line integral of the electric force E. Hence the line integral of E round the boundary is equal to the surface

[5] In Mr. Oliver Heaviside's system of rational units the 4π would be omitted and the relation between D and E expressed by the equation $\mathrm{D} = \mathrm{KE}$.

integral of $-\frac{d\mathsf{B}}{dt}$ (or of $-\dot{\mathsf{B}}$, as we may write it) over the area. Therefore it follows that $-\dot{\mathsf{B}}$ is the curl of E, or the time rate of decrease of the magnetic flux is the curl of the electric force.

But since $\mu\mathsf{H} = \mathsf{B}$, we may write the above equation in the form—

$$-\mu\dot{\mathsf{H}} = \text{curl } \mathsf{E} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Again, if round an electric current we describe any closed line, the line integral of the magnetic force along that line is equal to 4πC, where C is the total electric current through the closed line. Maxwell laid down as a fundamental principle that when change of electric displacement through a dielectric takes place, the change, *whilst taking place*, produces all the magnetic effect of a current. Hence, if we denote the rate of change of electric displacement with time by the symbol $\dot{\mathsf{D}} = \frac{d\mathsf{D}}{dt}$, then the total displacement is the surface integral of D, and the effective current is the surface integral of $\dot{\mathsf{D}}$. Accordingly, when dealing with a pure dielectric, we may, in accordance with Maxwell's postulate, consider that the time rate of change of the total displacement produces a magnetic force embracing it, and that the line integral of this magnetic force is equal to 4π times the total displacement current surrounded. Hence the surface integral of $4\pi\dot{\mathsf{D}}$ is equal to the line integral of H, or $4\pi\dot{\mathsf{D}}$ must be the curl of H. But since $\mathsf{D} = \frac{\mathrm{K}}{4\pi}\mathsf{E}$, it follows that $4\pi\dot{\mathsf{D}} = \mathrm{K}\dot{\mathsf{E}}$, and accordingly $\mathrm{K}\dot{\mathsf{E}}$ is the curl of H, or—

$$\mathrm{K}\dot{\mathsf{E}} = \text{curl } \mathsf{H} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Putting together equations (3) and (4), we see that there is a direct and a cross relation between E and H, as follows:—

$$\left.\begin{aligned} 4\pi\mathsf{D} &= \mathrm{K}\mathsf{E} \\ \mathsf{B} &= \mu\mathsf{H} \\ 4\pi\dot{\mathsf{D}} &= \mathrm{K}\dot{\mathsf{E}} = \text{curl } \mathsf{H} \\ -\dot{\mathsf{B}} &= -\mu\dot{\mathsf{H}} = \text{curl } \mathsf{E} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

These equations are the fundamental equations connecting the so-called forces, fluxes, and qualities of the dielectric medium.

Suppose that we apply them to a very simple case. Let the vector E be everywhere parallel to itself and its direction taken as the x axis. Let the vector H be at right angles to E and its direction taken as the y axis (see Fig. 1).

Also let the value of E and H increase as we proceed along the axes away from the origin.

To calculate the curls of these forces we have to take line integrals of them round elementary areas, $dxdy$, $dydz$, $dzdx$, in the counterclockwise directions.

Then the curl of E in the plane xz is $\frac{d\mathsf{E}}{dz}$, and in the plane of yx is $-\frac{d\mathsf{E}}{dy}$, and in the plane of yz it is zero. Similarly, the curl of H is zero for the plane xz. For the plane yz it is $-\frac{d\mathsf{H}}{dz}$, and for the plane yx it is $\frac{d\mathsf{H}}{dx}$.

Consider the plane perpendicular to the direction of H, viz. the xz plane. The curl of E for that plane is $\frac{d\mathsf{E}}{dz}$. Also consider the plane perpendicular to the direction of E, viz. the yz plane.

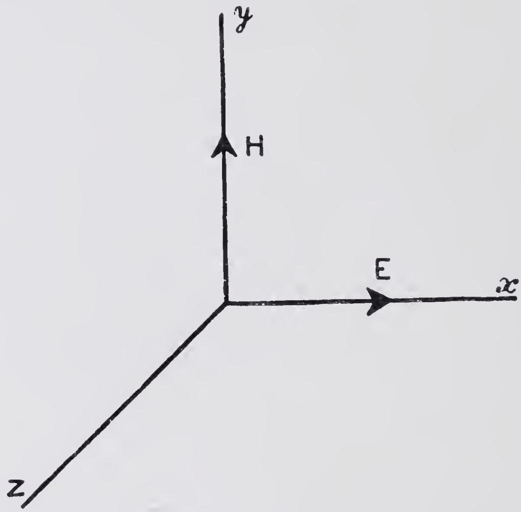


Fig. 1.—Electric and Magnetic Vectors at Right Angles.

The curl of H for that plane is $-\frac{d\mathsf{H}}{dz}$. Therefore, substituting in the general equations (5), we have—

$$\left.\begin{aligned} \mathrm{K}\frac{d\mathsf{E}}{dt} &= -\frac{d\mathsf{H}}{dz} \\ -\mu\frac{d\mathsf{H}}{dt} &= \frac{d\mathsf{E}}{dz} \end{aligned}\right\} \qquad (6)$$

Differentiate these equations with respect to z, and with respect to t, and equate results. We obtain—

$$\frac{d^2\mathsf{H}}{dz^2} - \mu\mathrm{K}\frac{d^2\mathsf{H}}{dt^2} = 0 \qquad (7)$$

$$\text{and } \frac{d^2\mathsf{E}}{dz^2} - \mu\mathrm{K}\frac{d^2\mathsf{E}}{dt^2} = 0 \qquad (8)$$

The above differential equations have general solutions of the form—

$$\mathsf{H} = f_1(z - ut) + f_2(z + ut) \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$\mathsf{E} = f_3(z - ut) + f_4(z + ut) \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where f_1, f_2, f_3, and f_4 are some functions of z and t and $u = \frac{1}{\sqrt{\mu K}}$.

These are well-known equations which indicate that **E** and **H** are wave motions propagated through space with a velocity u, since they remain unchanged if for z we put $z + z'$ and for t we put $t + t'$, provided $\frac{z'}{t'} = u$. In other words, the electromagnetic disturbance reaches a point at a distance z' further on in a time t', such that $z' = ut'$, and u is therefore the velocity of propagation. The matter may be put verbally thus: The characteristic of a wave of any kind is that the same physical events are taking place at the same moment at places separated by a distance called a wave length. Also the changes are periodic or cyclical both in space and in time. It is obvious from equations (9) and (10) that the periodic quantities **E** and **H** are in step or in phase with each other, both varying periodically and arriving at their maximum values at the same instant.[6]

The above equations may be generalized for space of three dimensions, as follows:—

Let X, Y, and Z be the components of electric force **E** at any point, measured in electrostatic units, and let α, β, and γ be the components of the magnetic force **H** at the same point measured in electromagnetic units. Then, since the unit of electrostatic electromotive force is 3×10^{10} larger than the unit of electromagnetic electromotive force, we can write the general equations connecting X, Y, and Z with α, β, and γ for any dielectric medium of dielectric constant K and permeability μ as follows: where A stands for $\frac{1}{u}$ and $u = 3 \times 10^{10}$, or is the velocity of light in centimetres per second and the unitary ratio. We have then—

$$\left.\begin{aligned} A\mu\frac{dx}{dt} &= \frac{dZ}{dy} - \frac{dY}{dz} \\ A\mu\frac{d\beta}{dt} &= \frac{dX}{dz} - \frac{dZ}{dx} \\ A\mu\frac{d\gamma}{dt} &= \frac{dY}{dx} - \frac{dX}{dy} \end{aligned}\right\} \quad . \quad (11) \qquad \left.\begin{aligned} AK\frac{dX}{dt} &= \frac{d\beta}{dz} - \frac{d\gamma}{dy} \\ AK\frac{dY}{dt} &= \frac{d\gamma}{dx} - \frac{d\alpha}{dz} \\ AK\frac{dZ}{dt} &= \frac{d\alpha}{dy} - \frac{d\beta}{dx} \end{aligned}\right\} \quad . \quad (12)$$

The above equations are in the form given by Hertz, and in writing them he follows conventions as to directions of axes, as follows. Suppose the origin of the co-ordinates to be within the head

[6] In reference to this matter, by some extraordinary oversight a misstatement was made in the first edition of the author's "Elementary Manual of Radiotelegraphy and Radiotelephony," where, on p. 125, the equation for **E** should have "cosine" written for "sine"; and on p. 126 the statement that **E** and **H** differ in phase by 90° is wrong. They are in phase or step with each other.

of the reader, then the x axis is directed straight away from you horizontally, the direction of the z axis is straight up, and the direction of the y axis is to the right hand. This plan differs from the usual English plan in that the z and y axes have changed places.

Suppose that we limit our consideration to space occupied only by æther, and take the permeability and dielectric constant to be unity. Then the equations (11) and (12) become—

$$\left.\begin{aligned} A\frac{d\alpha}{dt} &= \frac{dZ}{dy} - \frac{dY}{dz} \\ A\frac{d\beta}{dt} &= \frac{dX}{dz} - \frac{dZ}{dx} \\ A\frac{d\gamma}{dt} &= \frac{dY}{dy} - \frac{dX}{dy} \end{aligned}\right\} \quad . \quad (13) \qquad \left.\begin{aligned} A\frac{dX}{dt} &= \frac{d\beta}{dz} - \frac{d\gamma}{dy} \\ A\frac{dY}{dt} &= \frac{d\gamma}{dx} - \frac{d\alpha}{dz} \\ A\frac{dZ}{dt} &= \frac{d\alpha}{dy} - \frac{d\beta}{dx} \end{aligned}\right\} \quad . \quad (14)$$

Also we have two equations of continuity—

$$\frac{dX}{dx} + \frac{dY}{dy} + \frac{dZ}{dz} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$\frac{d\alpha}{dx} + \frac{d\beta}{dy} + \frac{d\gamma}{dz} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

which express the fact that there is no discontinuity in the electric and magnetic force in the region considered.

From the above equations it is easy to deduce by differentiation and substitution six others, viz.—

$$\frac{d^2\alpha}{dt^2} = \frac{1}{A^2}\left(\frac{d^2\alpha}{dx^2} + \frac{d^2\alpha}{dy^2} + \frac{d^2\alpha}{dz^2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

and similar ones for β and γ.

$$\text{Also} \quad \frac{d^2X}{dt^2} = \frac{1}{A^2}\left(\frac{d^2X}{dx^2} + \frac{d^2X}{dy^2} + \frac{d^2X}{dz^2}\right) \quad . \quad . \quad . \quad (18)$$

and similar ones for Y and Z.

This equation may be written symbolically thus—

$$A^2\ddot{X} = \nabla(X), \text{ where } \nabla \text{ stands for } \left(\frac{d^2}{dx^2} + \frac{d^2}{dy^2} + \frac{d^2}{dz^2}\right)$$

and similar ones in β and γ and Y and Z. These equations are the general differential equations for the propagation of a disturbance of any type with finite velocity $\frac{1}{A}$ through a medium, and they are similar to those which can be obtained in the case of a disturbance or wave propagated through air or water.

These equations are the simplest mathematical expression of the fact that the æther is a continuous medium, which can everywhere exhibit two physical effects, or can experience two correlated changes, one due to electric and the other to magnetic force. We may accept this as an ultimate fact, or we may try to picture to ourselves some form of mechanical movement or displacement constituting these

changes. In any case these changes are not independent of each other. The occurrence of one brings into existence the other, and the creation of electric or magnetic force at one point results in its propagation through space with the velocity of light.

Thus, if we suppose that we have a steady electric current in a wire, then this involves a distribution of magnetic force throughout space, along certain closed lines. If we imagine this current suddenly reversed in direction, then the reversal of the direction of the magnetic force due to it at points in space about 3×10^{10} cms., or nearly 1000 million feet away, would not take place at the same moment as the reversal of the current, but one second later. During that time (one second) the reversal of the direction of the magnetic force would be travelling through space as a change in the medium. Hence it follows that, when we are concerned with currents which are changing their direction very often or quickly, as in the case of electric oscillations, we are also concerned with rapid changes in the surrounding medium, which are travelling through it with the velocity of light.

This at once suggested to Maxwell that what we call light is, in fact, an electromagnetic phenomena. On this hypothesis, along the path of a ray of light we must have electric and magnetic forces normal to each other and to the direction of propagation of the ray, which are varying rapidly in a periodic and connected manner, and hence giving rise to waves travelling with the electromagnetic velocity.

3. Maxwell's Law connecting Dielectric Constant and Refractive Index for Electromagnetic Waves.—Maxwell's next step was to make a further deduction from these equations. We know that light moves through any transparent body, say water, more slowly than through empty space, as shown by actual experiment, and the ratio of the velocity in space to the velocity in water is called the *refractive index* of the water. Hence, if the velocity of electromagnetic waves in space is measured by $\frac{1}{\sqrt{\mu K}}$, where K and μ are respectively the dielectric constant and permeability of vacuous space, it is a legitimate deduction that the velocity through water will be represented by $\frac{1}{\sqrt{\mu' K'}}$, where K′ is the dielectric constant and μ' the magnetic permeability of water. Accordingly, the refractive index of water for the electromagnetic waves will be numerically measured by the ratio of—

$$\sqrt{\mu' K'} \text{ to } \sqrt{\mu K}$$

Experiment shows that the permeability μ' in the space occupied by water is not sensibly different from the permeability μ of empty space. Hence, if we take the dielectric constant of space arbitrarily to have a value unity, we should have a relation between the dielectric constant of water and its refractive index (i) as follows :—

$$i = \frac{\sqrt{K'}}{\sqrt{K}}$$

or if K is taken as unity, then the dielectric constant of water should

be equal to the square of its refractive index for electromagnetic waves.

The same argument applies to all other transparent and refractive dielectrics, and it therefore becomes a test of Maxwell's theory to examine how far the above law (called Maxwell's law) holds good. At the time when Maxwell published his theory there were very few data by which to test it, but in the last twenty years an immense number of methods of measuring dielectric constants have been invented, and a great number of numerical measurements have been made for various substances under different conditions of temperature and frequency, or time of application of the electric force.

Also direct measurements have been made of the refractive index of various substances for electromagnetic waves of various wave lengths. But at that date (1865-1866), and for some years afterwards, the only measurements of refractive index which had been made were those for the very short wave lengths constituting light or eye-affecting electromagnetic radiation. On comparing together the measured value of the dielectric constant of each of the few optically transparent dielectrics with the square of its refractive index for rays of light, it was found that the discrepancies were more numerous than the agreements. The dielectric constants had generally been measured by comparing the ratio of a steady or slow period alternating electric force, E, with the corresponding electric displacement, D, so as to obtain K from the equation—

$$D = KE, \text{ or } K = \frac{D}{E}$$

If this experiment is tried, for example, with water, with steady or even fairly rapidly reversed electric displacements, we get a value for K not far from 80, and for most varieties of glass we obtain values of K varying from 6 to 10. The optical refractive index of water, however, is 1·336, and that of most kinds of glass from 1·5 to 1·6 or more; hence it is clear that for these substances there is an enormous discrepancy between the square root of K (namely, 9 and 2·5 or 3·1) and the optical refractive indices (namely, 1·3 and 1·8).

More extensive research has shown that there are many substances for which we obtain, however, a fairly good agreement between the two numbers. Hence we may divide all dielectrics broadly into two classes, one including those substances which comply fairly well with Maxwell's law, and the other those cases in which there are great discrepancies between the value of the dielectric constant and the square of its optical refractive index.

In view of the extreme importance of the interconnection between refractive index and dielectric constant as a test of Maxwell's theory, it is desirable to discuss briefly the nature of these apparent exceptions to Maxwell's law. Investigation has shown that the values determined for dielectric constants are immensely affected in many cases by temperature and by the time of application of the electric force. Also it is known that refractive index is greatly affected by the frequency.

Dealing first with the effect of temperature on dielectric constant, a somewhat extensive examination has been made of the effect of low

temperatures on dielectric constants. One of the substances examined with great care by Sir James Dewar and the author was liquid oxygen. Sir James Dewar long ago showed that this substance had remarkable magnetic qualities, and a preliminary measurement made by us showed that its magnetic permeability had a value exceeding that of saturated ferric chloride.

As liquid oxygen is transparent, and as its refractive index had been carefully determined by Professor Liveing and Sir James Dewar, it was evidently desirable to measure its dielectric constant carefully. This was done by means of the commutator method already explained, using a small aluminium condenser consisting of seventeen plates, which could be immersed in a vessel full of liquid oxygen. The result was to show that liquid oxygen has a dielectric constant 1·491.[7] The capacity of the small condenser with air as its dielectric at 15° C. was 0·001030 mfd. The above value has been substantially confirmed more recently by a measurement made by Dr. Fritz Hasenoehrl, at the University of Leyden, his value for the dielectric constant of oxygen being 1·465.

The refractive index of liquid oxygen for two cadmium lines having a wave length respectively 4416 and 6438 was determined by Professor Liveing and Sir James Dewar to be 1·2249 and 1·2211.

Calculating from the above measurements, the value of the refractive index for waves of infinite wave length, we obtain the value 1·2181. The magnetic permeability of liquid oxygen was determined by a direct method, consisting in the immersion of a small air core transformer under the surface of liquid oxygen.[8] The value thus obtained for the magnetic permeability of liquid oxygen was 1·00287.

A more recent and very careful measurement of the susceptibility of liquid oxygen, made by an entirely different method by Sir James Dewar and the author, showed that the value of the magnetic susceptibility of liquid oxygen is 323×10^6, and that therefore its permeability is equal to 1·0041.

If we take the value of the square of the index of refraction of liquid oxygen for waves of infinite wave length, we obtain the number 2·4837; if we take the product of the dielectric constant of liquid oxygen as determined by Fleming and Dewar, namely, 1·491, and the value of its permeability as obtained by the direct method, namely, 1·00287, the product of these numbers is 1·395. If we take the best value of the magnetic permeability as determined by the experiments on the susceptibility of liquid oxygen (namely, 1·0041), and take the mean value of the dielectric constants as determined by Fleming and Dewar and Hasenoehrl, which is 1·478, we find the value of the product of 1·478 and 1·0041 to be 1·484, which agrees almost precisely with the value of the square of the refractive index of liquid oxygen for waves of infinite wave length, namely, 1·4837, as determined by the experiments of Liveing and Dewar.

This remarkable equality in the case of liquid oxygen between i^2, or the square of optical refractive index for waves of infinite wave

[7] See Fleming and Dewar on "The Dielectric Constant of Liquid Oxygen and Liquid Air," *Proc. Roy. Soc.*, 1897, vol. 60, p. 358.

[8] See Fleming and Dewar on "The Magnetic Permeability of Liquid Oxygen and Liquid Air," *Proc. Roy. Soc.*, 1896, vol. 60, p. 283.

length, and the numerical product of the value of its dielectric constant K and the magnetic permeability μ, is a very interesting confirmation of Maxwell's theory.

We have in liquid oxygen a substance which possesses four qualities found together in no other substances, namely, optical transparency, almost perfect non-conductivity, a magnetic permeability greater than unity, and a dielectric constant nearly 50 per cent. greater than that of empty space.

We turn, then, again to the question of the discrepancies, and ask, How is it that such substances as water, alcohol, æther, and glycerine, which in their pure condition are all good insulators, and therefore dielectrics, and optically transparent, show such marked disobedience to Maxwell's law? A careful investigation of this point has shown that temperature is largely accountable for the discrepancy.

By means of the cone condenser described in Chap. II., Sir James Dewar and the author have measured the dielectric constant of ice, frozen alcohol, frozen glycerine, and numerous other organic or inorganic frozen liquids, and have discovered that in all cases cooling them to a very low temperature destroys entirely these high dielectric values.

Thus, for instance, if the dielectric constant of ice is measured with an electric force applied either continuously or alternating 1 to 200 times a second, the temperature of the ice being 0° C., the value of the dielectric constant found is represented by a number in the neighbourhood of 80. If, however, the ice is cooled down to the temperature of liquid air, the dielectric constant of the ice falls to a value near to 2·4.

In the same manner, if the dielectric constant of alcohol is measured at ordinary temperatures, the number is found not very far from 25, but if the alcohol is frozen and cooled to the temperature of liquid air we find by the above-described methods a value 3·12.

Again, the dielectric constant of glycerine determined at ordinary temperatures gives a value 56, but if determined at the temperature of liquid air, a value 3·9.

If we gather into one table (see Table II., p. 355) the results of a number of these low-temperature measurements of dielectric constants taken at a frequency of 120 per second, and arranged so as to show the values of the dielectric constant at 15° C. and at −185° C. (the temperature of liquid air), we see at once the immense influence which temperature has upon the fundamental qualities of a dielectric. For the sake of comparison, the values of the square of the optical refractive index (i^2) for very long wave lengths or for certain wave lengths in the visible spectrum have been placed in contiguity.

The conclusions to which the figures in Table II. lead us is that, whereas at ordinary temperatures there is an enormous difference between the dielectric constants of certain substances and the square of their optical refractive index, a continual lowering of the temperature destroys a large part of this disagreement.

On the other hand, there are some substances for which, even at ordinary temperatures, Maxwell's law is very approximately fulfilled as shown in Table III. (see p. 355).

TABLE II.

Dielectric Constants (K) at Different Temperatures.

Substance.	K at 15° C.	K at −185° C.	Square of refractive index (i^2)
Water	80	2·4 to 2·9	1·779 (for D line)
Formic acid	62	2·41	—
Glycerine	56	3·2	—
Methyl alcohol	34	3·13	—
Mononitrobenzol	32	2·6	—
Ethyl alcohol	25·8	3·11	1·831
Acetone	21·85	2·62	—
Ethyl nitrate	17·72	2·73	—
Amyl alcohol	16	2·14	1·951
Aniline	7·51	2·92	—
Castor oil	4·78	2·14	2·153
Ethylic æther	4·25	2·31	1·805
Olive oil	3·16	2·18	2·131
Carbon bisulphide	2·67	2·24	2·01

TABLE III.

Substance.	Dielectric constant, K, at 15° C.	Square of optical refractive index (i^2).
Sulphur	4·73	4·89 (for B line)
Paraffin	2·29	2·022
Petroleum	1·92	1·922
Petroleum oil	2·07	2·075
Turpentine	2·23	2·128
Benzine	2·38	2·26 (for D line)

Exceptions, however, are more numerous than accordances, and we find no apparent fulfilment of the law in the case of the following substances :—

TABLE IV.

Substances.	K	i^2.
Glass (light flint)	6·57	2·375 (for B line)
Glass (dense)	10·1	2·924
Calcite	7·7	2·734 (for A line)
Fluorspar	6·7	2·05
Mica	6·64	2·526
Quartz	4·55	2·41
Tourmaline	6·05	2·63
Rock salt	5·85	2·36

In the case of gases there is a very fair agreement between K and i^2.

Then, with respect to the question of frequency, it has been found that the rate at which the electromotive force is applied and removed, or reversed, has a great influence upon the dielectric constant. Generally speaking, we may say that the higher the frequency the lower the dielectric constant. On the other hand, many substances exhibit, so to speak, a great constancy under variation in frequency.

By the employment of electrical oscillations, it is possible to determine the dielectric constant with very rapid alternations of electric force. It appears, however, that whether we use a continuous electric force or an electric force slowly alternating or even alternating 30,000 million times a second, the dielectric constant of water is still a number not far from 80. On the other hand, in the case of alcohol the same variation in frequency reduces the dielectric constant from 25 to about 6·6. Ice is more sensitive to change in frequency than water, and an increase in the frequency which does not affect the dielectric constant of liquid water reduces that of ice to a value between 2 and 5.

In considering the causes of the discrepancies, it is obvious that if light waves consist of alternations of electric force, then, since the visible spectrum is comprised between the limits of 400 and 800 billion vibrations per second, there is an enormous gap between the highest frequencies it is possible to command in experimentally measuring dielectric constants and the frequencies which give rise to optical effects. The whole of these effects give us reason to consider that the numerous discrepancies and exceptions to Maxwell's law are really dependent upon temperature and frequency.

It is obvious that in making comparisons we can hardly expect to find the law fulfilled unless the alternations of electric force, with which we determine the dielectric constant, are comparable with the number of vibrations per second in the ray by which the refractive index is measured.

Of late years it has been possible to test the matter in another way. We are now able, as will be explained below, to produce electric waves which are known to have all the properties of light, except visibility. Many recent investigations have had for their object the determination of the refractive index of water, alcohol, and other bodies for electric waves of great length lying far beyond the region of the ultra-red spectrum. For water the refractive index found for these electric rays is a number in the neighbourhood of 8·9.[9] The square of this number 8·9 is very nearly 80, and hence is in very good agreement with the value of the dielectric constant of water determined by purely static electrical methods, and either with continuous electric force or electric forces very slowly alternating.

It is impossible to dismiss this part of the subject without raising one question: Why is it that certain kinds of matter have such exceptionally large dielectric constants, which at ordinary temperatures are so different in value from the square of the optical index of refraction? The answer to this is, that electric force produces two effects when acting on any space occupied by dielectric matter. In

[9] See Fleming and Dewar, *Proc. Roy. Soc. Lond.*, 1897, vol. 61, p. 2, "On the Dielectric Constants of Ice and Alcohol at very Low Temperatures."

the first place, it creates an electric strain in the æther, or true electro-magnetic medium, which strain is immediately responsive to the stress.

In the next place, it operates on the molecules of the matter, producing an additional strain or displacement; and it is not a little remarkable that those substances which have high dielectric values are those which easily suffer chemical decomposition by displacement or removal of some radicle.

Some interesting facts connected with dielectric constants of solids and liquids have been noted by C. B. Thwing.[10] He has pointed out that, for a large number of substances, the dielectric constant is 2·6 times the density, and that the dielectric constant can be predetermined for many substances by calculation.

The dielectric constant of a body can be calculated by an addition law, in accordance with the following rule:—

The product of the molecular weight of the substance and its dielectric constant divided by its density is equal to a sum formed by multiplying 2·6 times the number of atoms of each kind by their atomic weight; except in the case when the molecule contains certain radicles, when each radicle has in addition a multiplying constant differing from 2·6.

Hence if K = dielectric constant;
M = molecular weight;
D = density;
a_1, a_2, etc. = atomic weights or elements of radicles;
n_1, n_2, etc. = number of atoms or radicles;

we have—

$$K = \frac{D}{M}(2{\cdot}6\, a_1 n_1 + 2{\cdot}6\, a_2 n_2 + \text{etc.} + k a_3 n_3 + \text{etc.})$$

The factor 2·6 is employed if the element is an atom of hydrogen, oxygen, carbon, etc., and the factor k if it is a chemical radicle OH, CO, COH, NO_2, CH_2, CH_3, or S, having values as follows:—

Radicle.	Molecular weight.	Value of k.
OH	17	80·6
CO	28	52
COH	29	33·8
NO_2	46	67·6
CH_2	14	2·86
CH_3	15	3·12
S	32	0·016

Thus the dielectric constant of water (H_2O), which is a hydride of hydroxyl, having molecular weight = 18 and density = 1, is given by the formula—

[10] See C. B. Thwing, *Zeitschrift Phys. Chem.*, 1894, vol. xiv. pp. 286–300.

$$K = \frac{1}{18}(2{\cdot}6 \times 1 + 80{\cdot}6 \times 17) = 75{\cdot}4$$

and that of ethylic alcohol (CH_3, CH_2, HO) by the formula—

$$K = \frac{0{\cdot}815}{46}(3{\cdot}12 \times 15 + 2{\cdot}86 \times 14 + 80{\cdot}6 \times 17) = 25{\cdot}6$$

These values agree with the results of experiments. This remarkable rule supplies us with a clue to the meaning of these large dielectric constants. We see that the presence in a molecule of a chemical radicle, or portion more easily detached than other atoms, seems to indicate a line of easy cleavage in the molecule of which the electric force takes advantage. It appears, therefore, that the simple properties of the electromagnetic medium filling space are profoundly modified by the presence of ordinary matter in the same place.[11]

Briefly, then, it may be stated that Maxwell's theory consists in the assumption that the effects we call electric displacement, or otherwise electric charge, and that which we call magnetic flux or magnetic induction, when they exist in a space free from ordinary gravitative matter, are affections of a medium capable of storing up energy in two different forms. The dielectric constant of the medium or the displacement per unit of electric force, and the magnetic permeability of the medium, or the magnetic flux per unit of magnetic force, are both altered by the presence of matter. The first quality is always increased, the second may be increased or diminished, and is enormously increased by the ferromagnetic substances.

These two qualities determine the speed of transmission of a disturbance or an electric wave through the medium, and an electric wave is created whenever a very sudden electric displacement is made or released. The moment, however, that we attempt to resolve the processes into mechanics, or the simple movement of matter possessed of inertia, and resisting some kind of change of configuration, we are met with many difficulties. The first question that presents itself is as to the nature of the elastic reaction of this medium against stress. What is the kind of deformation the medium resists? It cannot be a simple compressional elasticity or resistance to change of volume, as in the case of air. That would imply that the ray could not be polarized, whereas in the case both of light and electric rays they can be or are polarized, or made non-symmetrical with respect to the direction of propagation. Can the elasticity, then, be a simple resistance to shearing or change of form? This elastic solid or jelly theory of the æther fails to meet requirements in many points.

Then a third hypothesis is that the elementary portions of this medium do not resist either compression or shearing, but resist absolute rotation round any axis. This rotational theory of the æther, due originally to MacCullagh and Kelvin, has been developed in great detail by Sir Joseph Larmor, who has shown that it meets

[11] The reader may be referred to an article by Sir J. J. Thomson, on "Electromagnetic Waves," in the Supplement to the 10th edition of the *Encyclopædia Britannica*, for a mathematical discussion of the cause of these large dielectric constants, and an explanation of the abnormality as due to the presence of free ions or electrons in the mass of the dielectric.

in many remarkable ways the demands of physical theory.[12] The temptation to try and construct a purely mechanical theory of the æther, in which displacements and fluxes are visualized as changes of configuration or motions, is very great.

We are unable to make for ourselves a mental picture of any physical processes which we cannot in the ultimate issue resolve into motion, either past or present. If we could resolve all the operations in the electromagnetic medium into mere motions of some substance possessing the single attribute of inertia, it would in one sense satisfy our minds.

But the æther, if it exists at all, must have many more functions (some, perhaps, yet unsuspected by us) than those of merely conveying vibrations. If that is the case, we may do well to refrain from attempting too much mechanical interpretation, and, whilst resting on the fact that the definite changes we call electric displacement and magnetic flux are directed, or vector changes in a universal medium, admit that the ultimate analysis of the nature and structure or æther, energy, and matter, will carry us far beyond the region of the ideas of motion, inertia, or force.

It may, however, be asked, How do the above statements afford proof that the optical æther is identical with the electromagnetic medium? So far all that we have passed under review has been proof that if electromagnetic effects are propagated from place to place with finite velocity, that velocity will be measured by the reciprocal of the quantity $\sqrt{\mu K}$, and it has been shown that this electromagnetic velocity in vacuum, air, other gases, also in certain liquids and solids, is equal to the measured velocity of light rays through that material.

Our conviction that the propagation of light through transparent matter is not an effect wholly or entirely due to matter alone, is based for one thing on the fact that the mean velocity of light coming to us from Jupiter's satellites is the same as the actually measured velocity of light in air at the earth's surface.

In like manner, the dielectric constant and magnetic permeability of the very best vacuum we can produce differ so exceedingly little from the same qualities of an air-filled space at ordinary pressure and temperature, that we cannot well believe these properties of the space are wholly due to the matter, if taking out all but one-millionth of the gravitative matter makes so little difference.

The demonstration that light has an undulating nature rests upon all the well-known facts of interference. The creation and similar properties of undulations having an electrical origin travelling through space with equal velocity, and exhibiting all the properties of visible light, has afforded more than ground for a suspicion; it has given an almost perfect proof that the basis, the undulating material, and the nature of that undulation must be similar in the two classes of phenomena.

4. Electromagnetic Waves.—We must next turn attention to the production of electromagnetic waves, or, as they are shortly called, electric waves, in dielectrics by means of electric oscillations.

[12] For an exposition of Sir Joseph Larmor's views, we must refer the reader to his book, "Æther and Matter," University Press, Cambridge, 1900.

There are one or two questions connected with wave production in general concerning which a little preliminary discussion may be useful. One physical characteristic of wave motion is that by it energy is conveyed entirely away from the wave-creating body and exists for a time stored up in a surrounding medium. Consider, for instance, the production of a compressional wave in air. If the hand or a fan is moved to and fro in the air, the mere production of this motion or change of motion in the material body absorbs energy. When it is so moved in a fluid such as air, the moving solid sets up vortex or rotational motions in the surrounding air, similar to those whirls which are seen on moving an oar or the hand through water, and these fluid motions also take up energy to produce them. If a fan is moved slowly through the air, all that happens is that the air in front passes round behind it, and in so doing air vortices are created. Energy is therefore absorbed not only in making changes in motion of the solid, but also is taken up in the surrounding medium in creating this vortex motion or movements in the air which cling to and surround the moving body.

A large part of the resistance of motion which a solid body experiences in passing through a fluid is due to this form of energy absorption by the fluid. A perfect fluid, or one without any quality of viscosity, could not have these vortex motions so set up in it by a body entirely submerged and moving steadily so as to create no waves. Hence, a perfect fluid offers no resistance to the motion through it of a solid.

If the solid oscillates or moves slowly through a fluid, the energy never dissociates itself entirely from the moving solid or the fluid in its neighbourhood. The energy, so to speak, travels with the vibrating body and exists where it is, or in proximity to it, and when its motion ceases the energy of motion of the fluid is frittered away into heat.

It is quite different, however, if a body is moved or vibrated very rapidly, so as to bring into play the inertia quality of the fluid. If, for instance, instead of moving somewhat slowly through the air, the fan or other body, such as a tuning-fork, is made to vibrate with considerable speed, and inertia and compressibility of the air come into play, with the result that we have a true wave produced, the air has not time to get out of the way of the moving solid, and thus, instead of moving round to the back of the vibrating body, it is suddenly compressed, and subsequently rarified and started into oscillations. Each portion of the fluid takes up successively the oscillatory motion or changes of pressure, and energy is conveyed entirely away from the moving body and its neighbourhood, and continues to exist in the medium as a wave long after the vibrating body which started it has come to rest.

Some at least of the energy imparted to the solid to set it in vibration is taken from it and handed on from point to point through the air.

The characteristic of a true wave is that in each portion of the medium the energy so being conveyed exists alternately as energy of strain or configuration and energy of motion, or in some form equivalent to these types of energy. Moreover, at a distance called a *wave length*

similar energy changes are taking place at the same time. The mathematical expression for a wave is merely a symbolical statement of this fact. Thus the expression—

$$y = Y \cos 2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)$$

is the algebraical method of denoting a wave of wave length λ and periodic time T, and it tells us that a periodic disturbance or oscillation travels forward with a velocity $\frac{\lambda}{T}$, since the value of y remains the same if for x we substitute $(x + x')$ and for t, $(t + t')$, provided that $\frac{x'}{t'} = \frac{\lambda}{T}$.

Accordingly, at two places separated by a distance x', the same motion will take place after a time t'.

This is easily seen if we note that—

$$\frac{x + x'}{\lambda} - \frac{t + t'}{T} = \frac{x}{\lambda} - \frac{t}{T}$$

provided that $\frac{x'}{t} = \frac{\lambda}{T}$.

The total energy of a wave can be shown to be at any moment half potential or configurational and half kinetic or motional. At each point in the medium cyclical changes of energy take place, and the disposition of either kind is periodic in space and time.

The term *wave motion*, therefore, has reference to this peculiar mode of transferring energy from place to place, and, as we have already seen, waves can exist in any medium which possesses two essential qualities. The first of these qualities is that some kind of vector or directed change made in it must tend to disappear if left to itself, and not only so, but in being created must call forth an opposition or resistance to its creation. In the second place, in disappearing, the change, whatever its nature, must tend to overshoot the mark and be reproduced in the opposite direction; in other words, there must be a persistence or inertia-like quality in connection with the change of deformation.

There may, therefore, be as many different kinds of waves as there are possible modes of deformation in extended media.

Take, for instance, the case of water. If the water has a free surface, this is a level surface, and tends to remain level. If the water is heaped up in one place and left to itself, it begins to regain its level; but it possesses inertia, and in so doing it overshoots the mark and creates a depression in the surface.

From this point, therefore, surface waves spread out which are changes in level, periodic in time and space. Again, a free water surface possesses what is called *surface tension*. The surface of any liquid offers a resistance to stretching like a sheet of indiarubber. If, therefore, a surface of water is slightly heaped up, the surface is stretched, and tends again to become level in virtue of this surface tension. Hence we can have, not only what are called *gravitational waves* on the free surface of water, but ripples or *surface tension waves*.

These latter may be seen to be formed when a fishing-line or thin rod is moved through water perpendicularly to the surface. Furthermore, water resists compression, and hence we can have produced in it *compressional waves*, not on the surface, but in the mass. Such waves are produced in water by an explosion taking place beneath the surface.

In every case, however, the velocity of propagation of the wave is measured by the square root of the ratio of two quantities, one being of the nature of an elasticity, and the other the density or mass per unit of volume. Moreover, in all wave motion the velocity of the wave is measured by the product of the wave length and the number of complete oscillations per second executed by any part of the medium through which the wave motion is travelling.

If V represents the wave velocity, n the frequency, and λ the wave length, then we have the relation $V = n\lambda$ as a fundamental equation connecting wave length and frequency.

In the case of solid bodies we can have another kind of wave not capable of being produced in liquids, namely, a *distorsional wave*. The special characteristic of a solid substance is that it resists shearing or being changed in shape. If, for instance, we give a twist to a rod of steel, it resists this type of distorsional deformation, but we cannot put a twist of the same kind upon a thread of honey or column of water.

Accordingly, we can have a great variety of waves in material media depending upon the fact that their parts possess inertia, and that they resist some kind of relative displacement. Thus, for example, we may have—

Gravitational or surface waves in liquids—due to the resistance of the surface to being made unlevel.

Capillary waves or ripples on the free surface of liquids—due to the resistance of the surface of the free liquid to stretching.

Compressional waves in the mass of a gas, liquid, or solid—due to the resistance to change of bulk or volume elasticity.

Distortional waves in solid bodies—due to the resistance to shearing, twisting, or other changes of a form of any element; in other words, to shape elasticity.

These preliminary remarks will pave the way for a consideration of the nature of *electromagnetic waves*, or, as they are generally called, *electric waves*.

Every dielectric possesses, as we have seen, two properties. It can have a physical state produced in it at any point called the electric displacement, and this corresponds to the production of a deformation or strain in an elastic solid. The medium resists by an elastic reaction the creation of this displacement, and when the electric force creating it is withdrawn, the displacement disappears; but as a displacement requires an energy expenditure to produce it, the law of conservation of energy necessitates that the displacement in disappearing shall give rise to energy in some other form. This it does by the creation of magnetic flux in a direction at right angles to itself, and the flux in turn in disappearing gives rise again to a displacement at neighbouring points in the same direction as that displacement, the vanishing of which gave rise to the flux. Hence we detect in

this operation an analogy with the case of a vibrating solid where mechanical stress gives rise to elastic strain, and strain in disappearing creates velocity or sets matter in motion, and hence reproduces the strain energy in a kinetic form. This, again, in virtue of inertia recreates a new strain in an opposite direction.

The process of alternating electric displacement and resulting magnetic flux repeated cyclically in space and time from point to point through the dielectric constitutes an electric wave, and the velocity of this wave is measured by the value of $\frac{1}{\sqrt{K\mu}}$ for that dielectric. By the velocity of the wave is meant the quotient of wave length by the periodic time.

In considering these matters, the question necessarily arises: What is it that constitutes an electric displacement in a dielectric? Maxwell never committed himself to any opinion as to the exact nature of the physical change which he called the electric displacement. Mr. Oliver Heaviside remarks paradoxically that the more general or more vague a physical theory, in one sense the more likely it is to be true, or perhaps we should say the less likely it is to be untrue. This vagueness, however, is felt by some students to be unsatisfactory; they want to know whether an electric displacement is to be considered as an actual motion, or a stretch, squeeze, or rotation of an æthereal medium or of the material dielectric. If told that not only do we not know, but that all theories on this matter are most probably wide of the mark, they are apt to feel a degree of disappointment. We are on safer ground when we are content not to demand too much detail at present, provided that our hypothesis is sufficiently definite to enable it to become the foundation of a mathematical analysis of the phenomena.

Mechanical analogies are helpful as a guide, but we may easily become slaves to an analogy or a catch phrase.

In order that we may create an electric wave, we have, however, to create a state, called, for the sake of definiteness, electric displacement in a dielectric, and to release that constraint very suddenly, just as to produce a compressional wave in air we have to produce or release very rapidly an air compression.

5. Hertz's Researches.—These ideas had been grasped with some degree of clearness prior to the publication of the celebrated memoirs in Wiedemann's *Annalen der Physik*, in which Hertz announced his discoveries to the world.[13] It is to him we are indebted for a new departure on the subject which brought it at one stroke within the region of experiment. Hertz equipped the secondary terminals of an induction coil with a species of Leyden jar or condenser which is now known as a Hertz radiator. This consists of a pair of metallic plates, or sometimes balls, having attached to

[13] Heinrich Rudolf Hertz was born at Hamburg, February 22, 1857, and died at Bonn on January 1, 1894. He graduated at the University of Berlin, and was a favourite pupil of Von Helmholtz. In 1885 he become professor at the Technical College of Karlsruhe, and it was there that his epoch-making investigations were begun. In 1889 he received a call to succeed Clausius at Bonn. In July, 1888, his most important memoir on electro-magnetic waves in air was published, and at once attracted general attention to his work.

them short rods ending in knobs placed a fraction of a centimetre apart (see Fig. 2). These knobs are connected to the secondary circuit of the coil. Hence, as the secondary electromotive force accumulates, the plates are brought to a difference of potential, and lines of electrostatic displacement stretch out from one part of the oscillator, which we will call the positive side, to corresponding points on the negative side. We have thus a strong electric displacement created along certain lines of electric force.

Corresponding to a critical value of the potential difference, the air insulation between the balls breaks down, and it becomes highly conductive. Then the whole radiator becomes one conductor for the

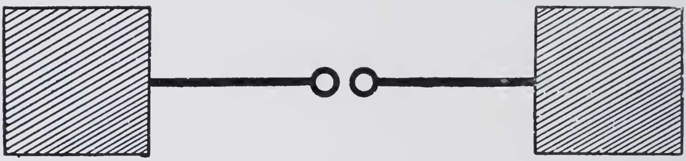


FIG. 2.—Hertz Radiator or Oscillator.

moment, and the potential difference begins to equalize itself, that is to say, a current flows from one side to the other, creating in the space around a magnetic flux, the direction of which is everywhere normal to the direction of the electric displacement. The electrostatic energy is thus transformed into electrokinetic energy. The flux then persists, and recreates in an opposite direction electric displacement. We may consider an illustration of the process as follows:—

Let a flat stretched steel spring represent the oscillator, and on it let a heavy disc be keyed like a wheel. Let the ends of the spring be fixed and the disc turned round, the spring thus being twisted. If then the wheel is released, it begins to move under the action of the torsional force. It acquires kinetic energy, and when the twist of the spring has disappeared, the wheel is possessed of all the energy as rotational energy. This then expends itself in reproducing the twist of the spring in the opposite direction.

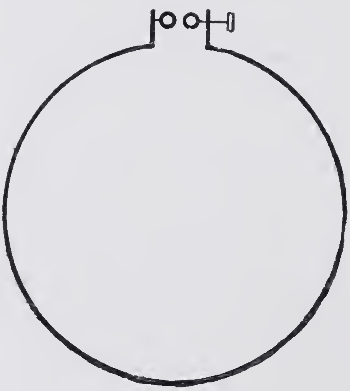


FIG. 3*a*.—Hertz Resonator or Receiver.

If the electric oscillation in the oscillator is started sufficiently suddenly, some of the energy is thrown off in the form of a displacement wave, and as a consequncee the oscillations of the radiator, as Bjerknes has shown, are quickly damped out. Accordingly, when the induction coil is kept going we have groups of intermittent oscillations, and therefore trains of electric waves thrown off which travel off or spread out through the dielectric.

Hertz furthermore devised a form of *resonator* for detecting these

electric waves at any point in space. In its simplest form this consists merely of a nearly closed ring of wire, the ends being provided with metallic balls placed very close together (see Fig. 3*a*). The ring may be a rectangle, and it may have a condenser inserted in its circuit, as in the arrangement due to Blondlot (see Fig. 3*b*). In order that we may secure the sharpness of breakdown in the air insulation which is necessary to obtain the oscillations, three things seem necessary.

First, the spark-ball surfaces must be bright and clean; secondly, no ultra-violet light rays must fall on the balls, especially on the negative terminal; and, thirdly, the balls must be at a certain distance apart, best determined by experience.

In describing experiments with the Hertz oscillator, we shall call the *axis of the radiator* the direction of the line joining the centres of the spark balls, and the line through the spark, perpendicular to this axis, will be called the *base line*. Also the line joining the spark balls of the resonator, will be called the *spark axis of the resonator*. If the resonator is set in front of the oscillator with its centre on the base line, then there are three principal positions which the resonator

Fig. 3*b*.—Blondlot Resonator.

may occupy. First, its plane may be parallel to the axis of the radiator and perpendicular to the base line: we shall call this the first position (see Fig. 4*a*). Secondly, the resonator may have its plane in the plane containing the radiator axis and the base line: we shall call this the second position (Fig. 4*b*). Thirdly, the resonator may have its centre on the base line and its plane perpendicular to the plane containing the radiator axis and the base line, and placed so that its plane passes through the spark gap: this will be called the third position (Fig. 4*c*).

Hertz found that when the resonator is placed in each of these three positions respectively, but not too close to the radiator, and if at the same time the resonator is turned round in its own plane so as to bring the spark axis of the resonator into various positions, different phenomena present themselves.

In the first place, if the resonator is placed in the first position, and with the spark axis of the resonator parallel to that of the radiator, then when the radiator is sparking, small sparks also occur between the spark balls of the resonator; but if the resonator is turned round in its own plane, so that the spark axis of the resonator is perpendicular to that of the radiator, then no sparks occur at the resonator.

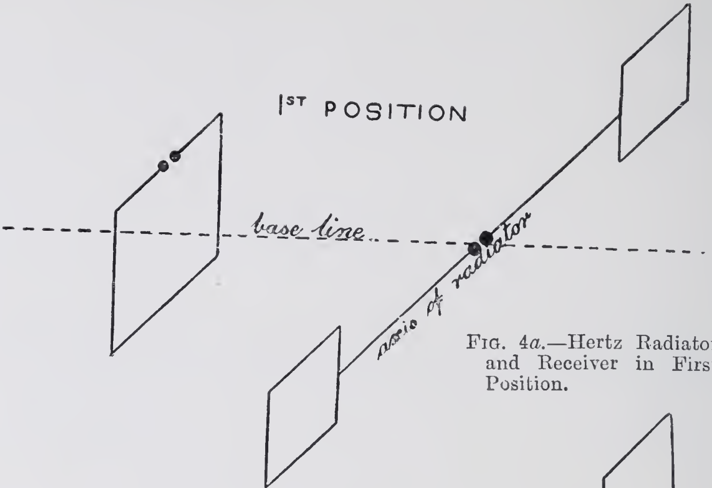


Fig. 4a.—Hertz Radiator and Receiver in First Position.

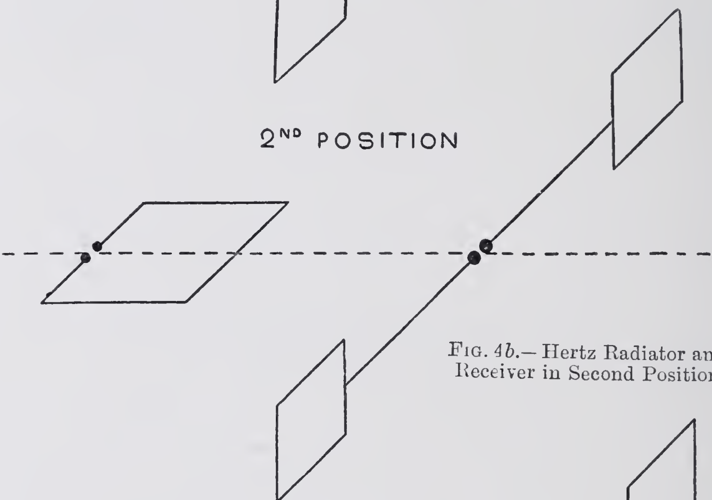


Fig. 4b.—Hertz Radiator and Receiver in Second Position.

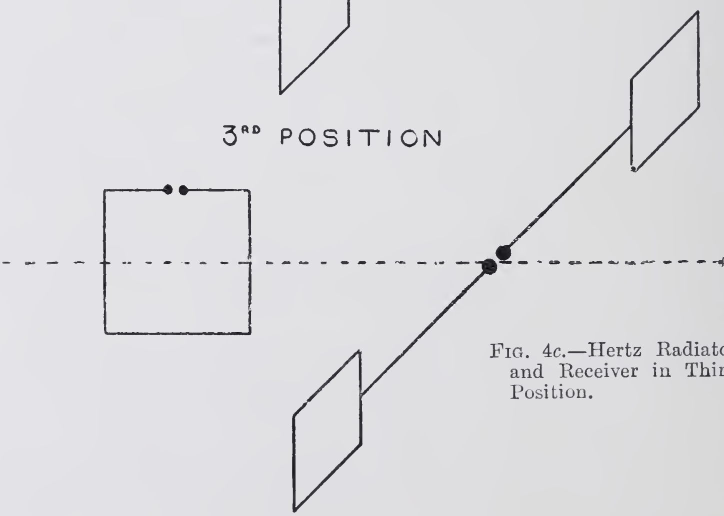


Fig. 4c.—Hertz Radiator and Receiver in Third Position.

In the next place, if the resonator is placed in the third position, with its plane perpendicular to the axis of the oscillator, then no sparks are seen, whatever the position of the air gap of the resonator.

When the resonator is placed in the second position, with its plane parallel to and passing through the axis of the radiator, then sparks are seen in the resonator air gap when that gap is turned towards the oscillator, but they become less and less bright as the resonator is turned round in its own plane until when the air gap is turned away as far as possible from the oscillator they cease altogether.

In order to explain this spark production in the resonator, it is necessary to make reference to a fact early discovered by Hertz.

If the resonator is attached by a wire to one terminal of the induction coil, then when the coil is in action, vigorous sparking is seen at the spark balls of the resonator, unless the connecting wire is attached to the resonator at a point symmetrical with respect to the spark balls. This is due to the inductance of the resonator circuit (see Fig. 5).

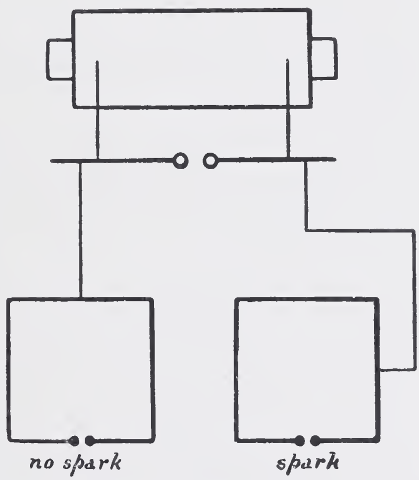


Fig. 5.—Hertz Resonator attached to One Terminal of the Secondary Circuit of an Induction Coil.

If the lengths of path measured along the resonator from the point of attachment of the wire to the spark gap are unequal, then, owing to their unequal inductance, the rise or fall of potential produced by the coil terminal takes effect first at the spark ball attached to the branch of smaller inductance.

One might at first be inclined to suppose that no difference of potential could be created between two balls connected by a short loop of wire, but although this is the case when low frequency oscillations are used, it is not so when the frequency is very high.

The same thing holds good when the resonator is not connected with the induction coil by a wire, but placed at a distance from the oscillator. In this case electric displacement produced by the radiator travels to the resonator through the dielectric. If the spark gap of the resonator is held parallel to the spark gap of the radiator, then the displacement or electric force arriving at the resonator fills the spark gap of the resonator and creates there an alternating displacement and an alternating potential difference between the balls. When this reaches a certain amplitude the air insulation breaks down, and a small spark is produced between the ball terminals of the resonator. Even although the resonator and the spark balls are connected by the resonator wire, this does not hinder the creation of the spark, as the

inductance of that wire makes it a practically perfect insulator to very suddenly applied potential differences.

If, however, the resonator is held in a position, so that the line joining the spark balls is in a direction at right angles to the spark axis of the oscillator, then no spark will occur in the resonator, because the electric force arriving there is not in a direction to create potential difference between the balls. If, however, the plane of the resonator is in the plane containing the base line and the spark axis of the radiator, and if the spark gap of the resonator is so placed that its direction is perpendicular to the axis of the vibrator, then feeble sparking is seen in the resonator. This, however, is because the electric force distribution is disturbed by the metallic circuit of the resonator.

The direction of the electric force, and therefore the displacement travelling through space, in the neighbourhood of the spark balls of the resonator is then no longer parallel to the spark axis of the radiator, but is slewed round so as to be inclined in a direction to the spark axis of the resonator. Hence the effect is to cause a displacement across the air gap of the resonator, and therefore to create a spark.

We may ask, then, what are the functions of the wire of the resonator if the spark formation is due to the action of electric force propagated from the oscillator? To answer this, we must analyze a little more closely what takes place in the resonator when the spark passes.

The resonator is a circuit possessing capacity and inductance, the spark balls forming, so to speak, the condenser portion of the circuit; hence it has a natural free period of electrical vibration. If in the space between the balls alternating electric displacement is produced, being propagated to that point through the dielectric, this displacement may or may not synchronize in period with the free period of vibration of the resonator. If it does time in with it, then the amplitude of the displacement oscillations is increased, and a point is reached at which the air insulation breaks down and a spark then passes.

Owing to the fact that the resonator is a nearly closed circuit, it is a very bad radiator, and, as Bjerknes has shown (*Wied. Ann.* 1891, vol. 44, p. 74), such a resonator has a very small coefficient of damping. If it is a circular resonator 35 cms. in diameter, as used by Hertz, it may even execute 1000 vibrations before the electric oscillations are practically damped out.

It is obvious, therefore, that oscillations can be most easily set up in the resonator circuit when the vibrations of electric displacement which give rise to these oscillations, propagated to the spark gap, are in a direction parallel to the spark axis of the resonator.

In the case in which the resonator is placed with its plane lying in the plane containing the axis of the radiator and the base line, the distribution of electric displacement is disturbed, as already explained, by the metallic circuit of the resonator, and the advancing wave surface of displacement has a component parallel to the spark axis of the resonator, and therefore the conditions are such as to be favourable to the production of at least feeble sparking.

Hertz's most famous discovery with the above described simple resonator was the proof he was able to give of the existence of stationary electric waves set up in a dielectric or in space bounded by a sheet of metal. He attached to his induction coil terminals a radiator composed of two square sheets of metal 40 cms. inside, having fixed to them rods ending in brass balls. These plates were arranged with the rods in one line and the balls about a centimetre apart, the direction of the rods being vertical (see Fig. 6). As a resonator he used a circular wire 35 cms. in diameter, with the ends nearly meeting and furnished with spark balls. A large sheet of metal was set up at the end of the room, and the radiator with axis vertical to it placed in front of this sheet. The resonator was held with its plane parallel

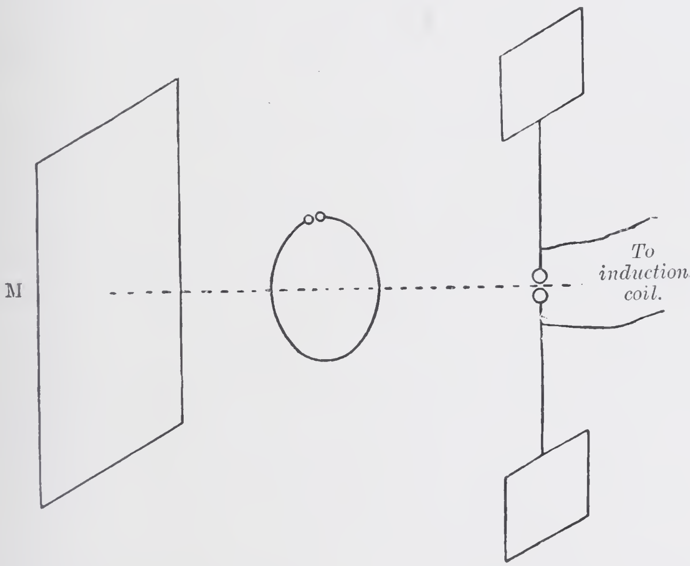


Fig. 6.—Hertz Resonator used to detect Electric Waves reflected from a Metal Sheet, M.

to the metal sheet, and its spark gap parallel to the spark gap of the radiator.

Under these conditions, if held near the metal sheet, no sparking occurred; but if moved away from it, sparks were seen, and at a certain distance these sparks had a maximum brilliancy; but if the resonator was removed still farther from the metal sheet, a position could be found in which the sparks again ceased.

All along the base line, therefore, perpendicular to the metal sheet, it was found that there were positions of maximum and minimum sparking indicating a periodicity in the distribution of electric force in that space.

A very important discovery in connection with this phenomenon was made by Sarasin and De la Rive (*Comptes Rendus*, March 31, 1891), who found that the distance between two non-sparking places

essentially depended upon the size of the resonator, and was approximately equal to four times the diameter of the circular resonator.

The earliest view taken of the effect was that the radiator creates stationary dielectric waves of definite wave length, and that the resonator indicates this wave length by sparking when held as described at places of maximum electric force. But it is found that the size of the radiator very little affects the result.

Another hypothesis was that the radiator sends out waves of all wave length, resembling, therefore, white light, and the resonator picks out and responds to its own particular wave length. But this hypothesis is not justified by any facts. The most probable explanation was that given by M. Poincarè, in 1891, and also by Professor Sir J. J. Thomson ("Recent Researches on Electricity and Magnetism," p. 402). The Hertz radiator, as shown by Bjerknes, is a very strongly damped system, and at each discharge hardly makes more than a dozen oscillations, even if so many, before its electrical vibrations are damped out.

Suppose the resonator, then, held at a distance from the metal wall equal to a quarter the wave length corresponding to this particular resonator, then, as the electric force passes over it, it will create a displacement between spark balls. This displacement travels on, is reflected from the wall, and returns. If it returns at such a moment as to assist the displacement, then, being made between the spark balls of the resonator, the amplitude of this displacement is increased, and a succession of such assistances will break down the insulation of the air and a spark will occur. It is clear, therefore, that this reinforcement of the displacement amplitude will occur when the distance of the resonator from the metallic wall is a quarter of its own wave length. Sarasin and De la Rive used resonators of various diameters (D), as shown in the table below, and measured the distance $\frac{\lambda}{2}$ between places of maximum sparking in the field.

TABLE V.

D	4D	Distance between two adjacent points of maximum sparking $= \lambda/2_1$
100 cms.	400 cms.	406 cms.
75 ,,	300 ,,	282 ,,
50 ,,	200 ,,	222 ,,
35 ,,	140 ,,	152 ,,
25 ,,	100 ,,	120 ,,
20 ,,	80 ,,	86 ,,
10 ,,	40 ,,	38 ,,

Accordingly, the distances between the positions of the resonator when the maximum sparking takes place in its air gap, reveal, not the wave length of pre-existing stationary waves, but the oscillation period or wave length corresponding to the resonator itself. Nevertheless, they prove the existence of stationary dielectric waves in the space between the metal sheet and the radiator, and therefore that the

electromagnetic impulses travel through space with a finite velocity. On referring to the last table, it will be seen that the wave length observed was very nearly equal to eight times the diameter of the circular resonator. Now, Mr. H. M. Macdonald has shown, in his book on "Electric Waves" (see p. 112), that by theory the fundamental wave length proper to a circular resonator is 7·95 times its own diameter. This singular agreement between theory and experiment shows that the resonator does not indicate the wave length of a train of waves of definite wave length passing through space, but that it is set in vibration by an electric impulse administered to it, and this calls forth its own natural proper vibration. The only satisfactory explanation of the phenomena is that which is based upon Bjerknes' discovery, that the oscillations sent out by the Hertz radiator are, as we have already seen, highly damped, whilst the oscillations of the nearly closed resonator are very slightly damped; hence the radiation proceeding from the radiator consists, at most, of half a dozen rapidly damped oscillations constituting each train, whereas the resonator, when set in vibration, may execute 1000 oscillations before they are extinguished. This fact has an important bearing upon the theory of the arrangements used in wireless telegraphy, as we shall see later on.

The Hertz resonator resembles the simple Marconi aerial in possessing a large radiation decrement, that is, its oscillations are highly damped by reason of radiation, whereas the receiving circuits employed are generally circuits having very small logarithmic decrements.

6. Repetition of Hertz's Experiments on Electric Radiation.—It is a difficult matter even to repeat Hertz's own experiments on this subject in a laboratory, and almost impossible to show them to a large audience. Nevertheless, the facts are so important, and an experiment shown is so much more valuable than a statement, that the author has devoted much attention to devising apparatus suitable for lecture purposes by which the principal facts of electro-optics can be shown even to large audiences. For this purpose he constructed a special form of radiator and receiver. The radiator consists of a zinc box, A, with one end closed, but open at the opposite end (see Fig. 7). From the sides of the box protrude zinc tubes. In these zinc tubes are fixed ebonite tubes, each of which contains a rod of brass 4 inches long, ending in a brass ball 1 inch in diameter. The rods are attached to long spirals of guttapercha-covered wire, which fill up the rest of the ebonite tube.

The rods are so fixed that the balls are held about a millimetre apart in the interior of the zinc box. The outer ends of the wire spirals are connected with the secondary circuit of an induction coil. When the coil is in action sparks pass between the balls and create electric waves about 8 inches in wave length, which issue from the open mouth of the zinc box. The use of the wire spiral at the end of the rod is to prevent the waves from travelling out at the side tube.

The receiver B (see Fig. 7) consists of a similar box containing a simple form of nickel-filings coherer, or electric wave detector. For the details and description of the mode of action of this device, called

the coherer, C, the reader must be referred to the next chapter. The wires in connection with the coherer are brought out through a metal pipe, which must be screwed or soldered into the box. This pipe is a couple of yards in length, and leads to an open metal box, in which is placed an electric bell, G, battery, B_2, relay, R, and relay battery, B_1, so joined up that when the metal filings in the sensitive tube became conductive, the relay is traversed by a current and sets the electric bell in action. The sensitive tube is restored to nonconductivity by

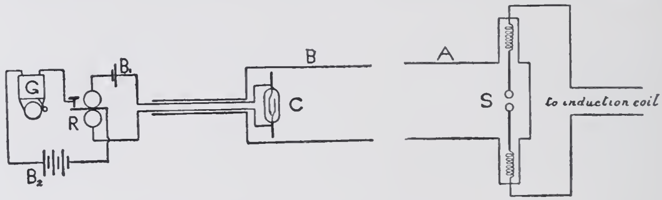


Fig. 7.—Apparatus for producing and detecting Electric Waves. S, spark balls in metal box, A, with open mouth; C, coherer in metal box, B, with open mouth; R, relay; G, electric bell; B_1, relay battery; B_2, electric bell battery.

giving the receiver box a smart knock with the fingers. The radiator box is held on a stand, so that it can be placed with its axis at any angle.

Furnished with this apparatus, we can generate a nearly parallel beam of electric radiation, the wave length of which is only about 8 inches. By its aid we can follow out a series of demonstrations, proving, as Hertz first showed, that this electric radiation is capable of reflection, refraction, and interference, and that various substances are opaque to it and others transparent. Moreover, this radiation, he showed, was stopped by a grating of fine wires placed with their direction parallel to that of the electric force or axis of the radiator. Since Hertz's experiments were made, many have traversed the same ground, and gleaned much additional knowledge.

It is now well known that to produce successfully on a moderately small scale optical effects with electrical radiation, it is necessary to employ radiators of small dimensions.

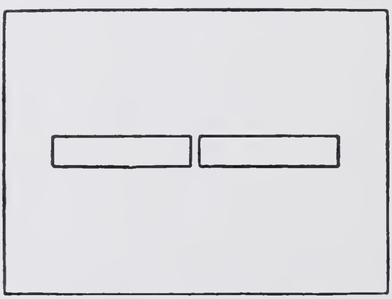


Fig. 8.—Righi Resonator.

Professor A. Righi, in 1894, described investigations made with an oscillator consisting of two metallic spheres 3·75 cms. in diameter, immersed in oil. These, when actuated by a large induction coil, produced electric waves 10·6 cms. in length. The resonator consisted of a piece of glass silvered along a certain strip 4 cms. in length, and one-fifth of a centimetre in diameter (see Fig. 8). Across the centre of this strip a minute scratch was made, forming the spark gap, and a microscope was employed to observe the tiny sparks in this spark gap.

With this apparatus, or with another circular or ring-shaped resonator formed in the same way of silver deposited upon glass, Righi obtained electrical equivalents of all the familiar optical facts, the resonator acting as an eye to detect the invisible radiation. Since that time other workers, such as Lebedew, Bose, and Lampa, have, by reducing the dimensions of the apparatus yet further, decreased the wave length of electrical waves to about 4 cms., and obtained electrical radiation the wave length of which is only fifty to sixty times longer than that of the longest heat rays which have been sifted out by repeated reflection from a luminous source of radiation, such as the Welsbach gas radiator.

This electrical radiation penetrates easily through dielectric bodies. It is completely reflected from metallic surfaces, and is also more or less reflected from the surface of insulators.

These facts can be easily exhibited with the above-described apparatus. If the radiator box and the receiver box are placed with their open ends towards each other and about a couple of feet apart, the axes being in the same straight line, we find that on pressing a key in the primary circuit of the induction coil the bell in the receiver circuit rings. If, however, a sheet of tin, or tinfoil, or even of silvered paper, is interposed, the radiation is cut off. A sheet of perforated zinc, a wet duster, and even the human hand or body, are found to be perfectly opaque. On the other hand, a slab of wood, paraffin, wax, pitch, glass, ebonite, leather, dry cloth, and all other insulators are transparent. Conductors of any kind are opaque. Amongst liquids, water, alcohol, glycerine, and amyl alcohol are also opaque; whilst paraffin oil, turpentine, bisulphide of carbon, and creosote are very transparent.

If we turn the radiator so that its open mouth is not directly towards that of the receiver, we find that the receiver is not affected, showing that the radiation is not entering it. We can, however, reflect the radiation into the receiver by using as a reflector a sheet of metal, a wet cloth, the hand, or a moist sheet of glass. We can easily prove that this radiation obeys the optical law, and that the angle of incidence is equal to the angle of reflection. All good reflectors are opaque to the radiation. It is curious to notice how much of the radiation is reflected from a sheet of window glass unless carefully dried. This is due to the film of moisture generally present upon it.[14]

By examining the reflection from dielectrics such as glass and paraffin, Professors FitzGerald and Trouton were enabled to settle the long-disputed question as to the direction of the vibration in relation to the plane of polarization in plane polarized light.

According to Fresnel, the luminous vibration was at right angles to the plane of polarization, that is, to the plane of reflection when light is polarized by reflection, whilst according to MacCullagh it is coincident with that plane.

The theory of electric waves indicates, as we have seen, that we are concerned with two vectors, one the magnetic force and the other the electric force, and that both these periodically vary. Theory

[14] Prof. Trouton has shown that in this case the reflection is really due to a film of moisture on the glass. There is no reflection from a sheet of perfectly dry glass.

indicates that the electric force is perpendicular to the plane of polarization. This conclusion was verified by FitzGerald and Trouton, for electric waves were found not to be reflected at the polarizing angle from the surface of a dielectric when the electric force is parallel to the plane of polarization; but reflection occurs at all angles when the electric force is perpendicular to that plane. In the electric ray, therefore, the electric force is perpendicular to, and the magnetic force parallel to or in, the plane of polarization.

Some of the most interesting results in the study of electric waves are those which have flowed from experiments made on the refraction of these electric rays. By the use of a colossal prism of pitch, having a refracting angle of 30°, Hertz was able to discern a refraction of 22° when long electric waves were incident on the prism, indicating a refractive index of 1·69. It is convenient to call the refractive index so determined the electrical refractive index, and the refractive index for luminous or visible light the optical refractive index.

With the author's apparatus, it is very easy to exhibit the power

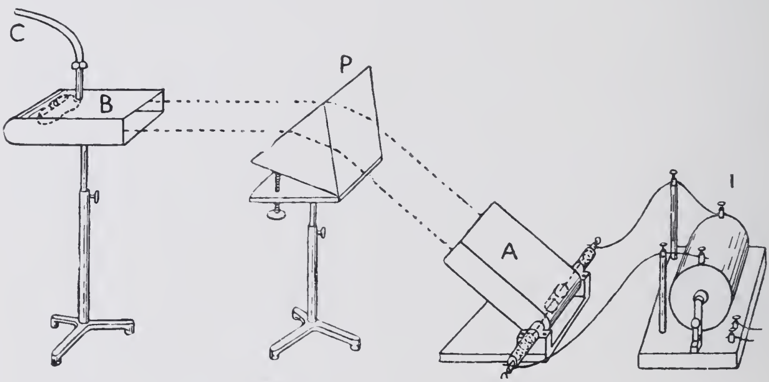


FIG. 9.—Refraction of an Electric Beam by a Paraffin Prism.

of insulators to refract this radiation with a prism of quite small dimensions. A paraffin prism having a refracting angle of 60°, the length of each side being about 6 inches, is constructed. If we set the radiator and receiver boxes in such positions that the electric ray emerging from the radiator just escapes the receiver, and so does not directly affect it, we shall find that on introducing the above-mentioned paraffin prism in the path the electric ray is refracted just as would be a ray of light by a glass prism (see Fig. 9). With a little care, it is easy to measure the deviation of the ray produced by the prism, and hence to calculate the electric index of refraction of the material. The author has, in this manner, measured with his apparatus the refractive index i of paraffin wax and also of dry ice, employing for this purpose a large ice prism, cut with the saw out of a block of ice. The refracting angle r of the paraffin prism was 60°, and the minimum deviation d of the electric ray produced by it was 45° to 50°. In the case of the ice, the refracting angle of the prism was 50°,

and the minimum deviation of the ray was also 50°. Hence, by the formula—

$$i = \frac{\sin\frac{r+d}{2}}{\sin\frac{r}{2}}$$

we have for the paraffin a value of the electric refractive index—

$$i = \frac{\sin\frac{60^\circ + 30^\circ}{2}}{\sin\frac{60^\circ}{2}} = \frac{\sin 55^\circ}{\sin 30^\circ} = 2 \sin 55^\circ = 1{\cdot}64$$

and for the ice—

$$i = \frac{\sin\frac{50^\circ + 50^\circ}{2}}{\sin\frac{50^\circ}{2}} = \frac{\sin 50^\circ}{\sin 25^\circ} = 1{\cdot}83$$

By Maxwell's law the squares of these indices should be equal to the dielectric constants. The square of 1·64 is nearly 2·7, and the square of 1·83 is nearly 3·34.

The values obtained by electrostatic methods for the dielectric constant of paraffin wax give numbers not far from 2. The values obtained for ice at or near 0° C., by low frequency on electrostatic methods, give values near 80. If, however, the ice is taken at very low temperatures (−190° C.), then for low frequency we find values of the dielectric constant near 3·0 and under. (See Fleming and Dewar, *Proc. Roy. Soc. Lond.*, 1897, vol. 61, p. 2, on the "Dielectric Constant of Ice at Low Temperatures.")

It is interesting to notice that M. C. Gulton (*Comptes Rendus*, 1900, vol. 130, p. 1119; or *Science Abstracts*, vol. 3, p. 545) has by another electric wave method, determined the electric refractive index of dry ice at a little below 0° C. He found the ice did not perceptibly absorb electric waves. He determined the refractive index to be 1·76, corresponding to a dielectric constant 3·1. The wave length used was 14 mm. He also measured the refractive index for waves of 25 cms. in length, and up to 2000 cms. He discovered that the electric refractive index progressively decreases from 1·76, corresponding to the 14 mm. waves, down to 1·50 for waves 2088 cms. in length. This last gives a dielectric constant of 2·25, which is not far from the value 2·0, found by M. Blondlot for still greater wave lengths. Hence the rather rough experiment made by the author with an ice prism gives a result for the dielectric constant which is not greatly different from those found by other electrical methods when the disturbing influence of temperature is eliminated. The observed values of the deviation of the ray by the prism used by the author are unquestionably only approximate values, as the radiation emitted from the radiator is far from being a well-defined ray. It is remarkable, in fact, that when dealing with radiation, the wave length of which is

so large compared with the dimensions of the prism, one should be able to obtain any well-marked refraction at all.

The author has also succeeded, with the same apparatus, in showing the total internal reflection of the ray by a right-angled prism of paraffin. Most interesting of all, however, is the concentration of the electric ray by paraffin lenses. It is easy to cast a plano-cylindrical lens of paraffin wax. The radius of curvature of the curved side may be 6 inches, and the focal length is then 12 inches. Two conjugate foci exist for such a lens (made of a material of refractive index 2), at equal distances of 24 inches on either side of the lens. If we place the radiator box and receiver box at a distance of 4 feet, we may so adjust the receiver that the direct radiation is too weak to cause the bell to ring. If we interpose the paraffin lens halfway between, it converges the radiation on to the receiver and creates an electrical focus at or near the sensitive tube or box, and the bell of the receiver at once rings (see Fig. 10). This shows

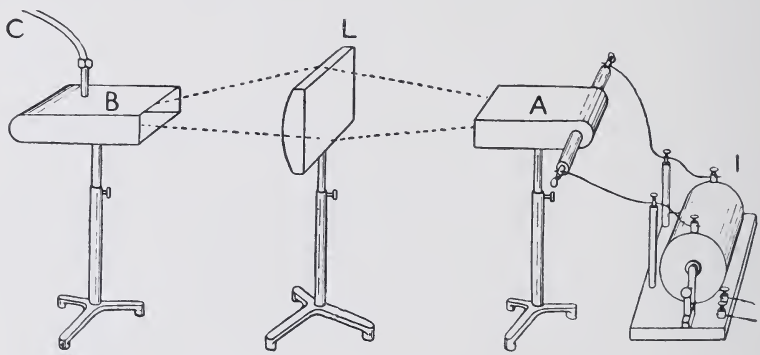


FIG. 10.—Convergence of an Electric Beam by a Paraffin Lens.

clearly that the paraffin lens gathers up the diverging electric radiation and focuses it on to the receiver.

With the same apparatus, interesting experiments can be shown illustrating the action of gratings on this electric radiation.

If we interpose in the path of the ray a grid made by winding wire over a frame (see Fig. 11), it is found that this grid is opaque to the radiation if the wires are held parallel to the electric force of the ray, but transparent if they are held parallel to the magnetic force. The reason for this seems to be that in the former case secondary electric currents are set up in the wires, and these shield the receiver from the original radiation, because the magnetic force of the induced current is exactly opposite in phase to the magnetic force of the original ray at that point where the wire is situated, and hence at the point where the coherer is situated, and accordingly a complete shielding takes place.

The author has found that a set of large pins, arranged parallel to each other at a little distance apart on a sheet of paper, acts in a similar manner; but a set of very small or midget pins similarly arranged is not an effective screen. The use of the small pins simply

amounts to the cutting up of a large wire into very short lengths, and this effectually prevents the induction in it of any sensible current.

A large number of different methods have been employed for determining the electrical refractive index of dielectrics. One of the most simple of these is to employ a Hertz resonator of rectangular form, having spark balls at the centre of one side, and a wire attached to the centre of the opposite side, this wire being connected to the secondary terminal of an induction coil. When the coil is set in operation, no sparks would then be found to occur at the spark balls of the resonator, because the electrical oscillations, starting from the point of origin, arrive at the spark balls by two different routes of equal length. If, however, one side of the rectangle is immersed in paraffin, sulphur, or any other dielectric, the equality is broken down and sparking would occur. This sparking can only be stopped by lengthening the opposite side of the rectangle so as to increase its inductance, and when this is the case the product of inductance and capacity of each side must be equal. Hence we can deduce the

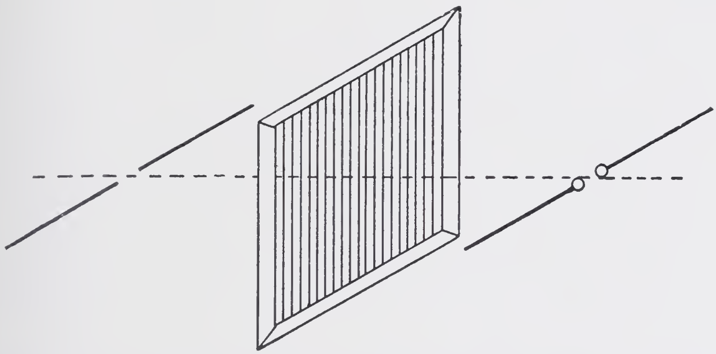


FIG. 11.—The Interposition of a Grid between Radiator and Receiver Rods to show Opacity or Transparency according to Position.

dielectric constant, and therefore the refractive index of the material in which one side of the rectangle is immersed.

Experiments of this kind made by Sir J. J. Thomson, to determine the electrical index of refraction of paraffin and sulphur, gave values respectively of 1·35 and 1·7, indicating dielectric constants equal to 1·8 and 2·9.

By a similar and more sensitive arrangement, Arons and Rubens found the electrical refractive indices of certain substances to be as follows:—

Castor oil	2·05
Olive oil	1·71
Xylol	1·50
Petroleum	1·40

The values for the electrical refractive index were found to be in fair agreement with the dielectric constants of the same substances, as determined by slow alternations of electric force.

Similar measurements have been made by A. D. Cole, by determining the reduction in wave length which occurs when the parallel

wires of a Lecher arrangement are passed through a trough containing liquid. Cole has measured in this way the electrical refractive index of water and alcohol (*Wied. Ann.*, 1896, vol. 57, p. 290).

In the first experiment, waves having a wave length of 300 to 600 cms. length in air were used. The wave length in water for the same frequency was about one-ninth part of the wave length in air, the exact ratio being 8·9, which is therefore the electrical refractive index of water. This number agrees very well with similar measurements by Drude, using waves of 60 cms. in length, which gave the value 8·7 for the electrical refractive index of water. The square of 8·9 is 79·21, which is almost identical with the value of the dielectric constant of water as determined by electrostatic methods, such as that employed by Heerwagen.

Electrical waves having a wave length of 209 cms. in air have been found to give for alcohol an electrical refractive index of 5·24, and the square of this last number agrees very well with the electrostatic or low frequency determinations of the dielectric constant of alcohol.

By employing short electric waves, 5 cms. or so in wave length, Cole was able to measure the electrical refractive indices of water and alcohol by an indirect method. A sheet of zinc, 1 mm. thick, is found to reflect the electric ray practically without loss at 45°, when the electric component is perpendicular to the plane of incidence. Measurements of the reflective power of a water surface at the same incidence (45°) show that the reflective power is 71·8 per cent. when the electric component is perpendicular to the plane of incidence. In this latter case the zinc surface would reflect 92 per cent.

By applying two formulæ due to Fresnel, the index of refraction can be determined from these data. For water the value deduced was 8·85, for alcohol the electrical refractive index lies between 3·15 and 3·25.

Hence, it appears that in the case of alcohol there is a rapid diminution in the refractive index as the wave length is shortened from 300 or 600 cms. to 5 cms., but for wave length variation over the same range little or no such diminution occurs in the case of water.

The above facts, however, show that in the case of both these fluids there must be considerable anomalous dispersion. It is well known that within the limits of ordinary visible spectrum a decrease in the wave length of the refracted light is accompanied by an increase in refractive index in the case of most transparent bodies.

For instance, when light passes through water, alcohol, or bisulphide of carbon, the waves which produce the sensation of violet light are shorter in wave length and have a larger refractive index, and are therefore more refracted than those which produce the sensation of red light. But this is not universally the case. Many substances are known, such, for instance, as an alcoholic solution of fuchsine, which possess anomalous dispersion, and for these substances the red rays are not less refracted than the violet; but the order of the colours in the spectrum is entirely changed. If light is passed through a thin prism formed with the above solution, the violet rays are found to

be less refracted than the red. This anomalous dispersion always accompanies great local absorption in the spectrum; and, as Kundt has pointed out, wherever there is a strong absorption band in the spectrum the refractive index is abnormally increased below the band and abnormally diminished above the band in going up the spectrum from the red to the violet.

In the case of water, the optical refractive index for waves having a wave length within the limits of the visible spectrum is a number lying between 1·4 and 1·3, a decrease in the refractive index within these limits corresponding to an increase in wave length. If, however, the incident wave length is increased in length up to 5 cms. or upwards by employing electrical waves, the refractive index rises to a number not far from 8·9, and all experiments show that when using electric waves having wave lengths between the limits of 6 metres and 6 mm., the electrical refractive index of water is a number not far from 8·9.

Hence, there must be a large fall in refractive index in passing from the frequency 6×10^{10}, corresponding to waves of 5 mm. in length, to the frequency of 400×10^{12}, corresponding to the waves which give rise to red light which have a wave length of about $\frac{1}{1300}$ mm.

Accordingly, it is clear that, in the case of water, when we select a sufficiently wide range of vibrations, there must be a marked anomalous dispersion. This may be connected with the strong absorption band which is known to exist in the case of water in the ultra-red spectrum.

For alcohol, it has been found that in passing from electric waves having a wave length of 8 or 9 metres to waves having a wave length of about 8 mm., the electrical refractive index drops from a value of 5 or thereabouts to a value of 2·5. In other words, the refractive index diminishes with the wave length; hence it is clear that here also there must be anomalous dispersion.

One of the results which has emerged from these investigations is the proof that is afforded by them of the fact that a change in frequency has a very much greater effect upon the electrical refractive index of some substances than others. Thus, as regards ice, it has been shown by M. E. Bouty that when using low frequency alternations of electric force, the dielectric constant of ice at $-23°$ C. and upwards has a value 78·8.[15] Dr. J. Hopkinson and Professor E. Wilson also made determinations of the same constant, and found that for alternations lying between 10 and 100 a second the dielectric constant of ice is a number of the order of 80.

M. Blondlot (*Comptes Rendus*, 1894, vol. 119, p. 595), using electric waves, has measured the electrical refractive index of ice and found a value of 1·41 for it, corresponding to a dielectric constant 2. The experiments of Dr. Hopkinson and Professor Wilson showed that the dielectric constant of ice measured with a frequency of a million is a number less than 3. Blondlot's value for the electrical refractive index of ice has been confirmed by A. Perrott (*Comptes Rendus*, 1894, vol. 119, p. 601), who found the value of 1·43 of the electrical refractive index.

[15] *Journ. de Physique*, 1892, vol. 1.

We see, therefore, that for even, comparatively speaking, very moderate increase in frequency the electrical refractive index of ice falls to a value nor far from that of its optical refractive index, whereas over the same range of frequency the electrical refractive index of water still maintains a value 8·9, which is far above the value of its optical refractive index. This and many other similar facts appear to show that when liquid dielectrics of high dielectric constant pass into the solid state, these abnormally large values of electrical refractive indices are more easily reduced to an approximation in value to the optical refractive indices by increased frequency than are those of the corresponding liquids.[16]

As regards glass, Bose has measured the index of refraction of glass for electric waves by a method resembling the optical method of total reflection due to Terquem and Trannin, using electric waves having a frequency of 10^{10} or a wave length of 3 cms. By four different methods he found a value for the electrical refractive index of glass close to 2·04; the value of the optical refractive index for the D rays for the same glass was 1·53. The dielectric constant of this glass, when determined by static methods, would probably have yielded a number not far from 6; the square root of its dielectric constant would probably have been a number lying between 2·5 and 3. Hence the electrical refractive index has a number approximating more closely to the optical refractive index than does the square root of the static dielectric constant.

Leaving out of account questions of the absorption of energy, the facts show then that electric waves travel very much more slowly through dielectrics than through empty space. In the case of water, the velocities in space and water are in the ratio of 9 to 1, for any electric wave lengths yet produced; whilst for visible light waves the ratio is more nearly 1·3 to 1. We find that for alcohol the wave velocity ratio is 5 to 1 for long electric waves, and 2·5 to 1 for the shortest electric waves yet produced; whereas for visible light waves the ratio is only about 1·3 to 1.

When, however, we select such substances as paraffin oil, turpentine, many hydrocarbons, liquid oxygen, or bodies of simple chemical constitution, we find no such great difference between the velocities of the electrical and light waves of very different wave length. Then, again, it has been shown that very low temperature annuls this difference in the velocity ratios for electric and eye affecting radiation.

An interesting question then presents itself for solution. We ask, why is it that water reduces the velocity of non-visible electric waves passing through it so much more, relatively speaking, than it does the velocity of visible light waves of much higher frequency. The answer to this question is, no doubt, to be found in the variation of dielectric constant with frequency. There are a large number of substances of simple symmetrical chemical constitution, such as the liquid gases, paraffins, saturated hydrocarbons, etc., which have all dielectric constants, lying in value between 2 and 3, and optical and electrical refractive indices lying between 1·4 and 1·7, and these values are but

[16] See Fleming and Dewar, "Note on the Dielectric Constant of Ice and Alcohol at very Low Temperatures," *Proc. Roy. Soc.*, vol. 61, pp. 2 and 316.

little disturbed by any change in frequency varying between zero and billions per second. It would seem as if the *matter* of which these bodies consist merely had the power of about doubling the dielectric constant of empty space or æther, without much changing the qualitative characteristics of the dielectric constant of the æther. We have seen that, according to Thwing's law, the dielectric constant of these bodies is nearly 2·6 times their density.

On the other hand, all bodies, the molecules of which contain those little groups of easily removed atoms which chemists call radicles, such, for instance, as hydroxyl, nitryl, etc., have dielectric constants more or less sensitive to change in frequency according to their temperature. An increase in the frequency generally, but not always, decreases the dielectric constant. Hence, as a rule, in these cases the electric displacement is larger for a given electric force the longer the time during which the force is applied. To elucidate these anomalies, Sir J. J. Thomson suggests the following theory.

The large dielectric constant of certain bodies, even under high frequency electromotive forces, implies that there is a corresponding large refractive index for waves of the same frequency. As a rule refractive index decreases as frequency decreases, hence large dielectric constants of such substances as water implies an abnormal refraction or a range of frequencies for which there is intense absorption. Thomson shows (see article, "Electromagnetic Waves," *Encyclopædia Britannica*, 10th edition) that this is due to the presence of a relatively small number of molecules in a special state. He expresses the opinion that the experiments of Dewar and Fleming on the effect of low temperature on the dielectric constants of numerous bodies are in harmony with this supposition, and that the effect of very low temperature on ice, glycerine, ethylic, alcohol, etc., must be to prevent that dissociation of some molecules which produce the bodies, the presence of which, when mixed with the ordinary molecules, gives rise to the abnormally large dielectric constants. Whatever may be the cause, the existence of these large dielectric constants is always dependent on the presence of certain chemical radicles in the molecules of the substance.

7. The Production of Electric Waves by Oscillations in an Open Circuit.—No method has yet been discovered by which an electric wave can be produced, except by means of the excitation of electric oscillations in an electric circuit possessing capacity and inductance. We must, therefore, study a little in detail the actions which take place when high frequency oscillations are set up in a linear circuit.

Let us consider the simple case of a pair of rods placed in one line with their ends (which should be smoothly rounded) placed a millimetre or two from each other (see Fig. 12). Let these rods be connected to the secondary terminals of an induction coil, or in any way brought to a difference of potential just sufficient not to pierce the air between their contiguous ends and made a spark. Then these rods are charged, one with positive and the other with negative electricity. There is, therefore, a distribution of electric strain in the space round the rods which very roughly may be represented as to direction by the dotted lines in Fig. 12. In the next place, suppose

the difference of potential increased until a spark passes. The rods just before that moment are in the condition of the two coatings of a condenser; in fact, they have a certain capacity with respect to each other, and a certain charge determined by that capacity and by their difference of potential. When the spark passes, this condenser begins to discharge with oscillations. We may regard these oscillations as due to the rapid movement to and fro in the wire of *electrons* or point-charges of negative electricity and the lines of electric strain as starting from and terminating on these electrons. Accordingly the oscillations are oscillations of the ends of the lines of electric strain where these abut on the wire or rod. The whole of the facts discovered by Hertz show that when a change is made in the direction or amount of the electric strain at any one point in the medium this change is not instantly felt at all points, but is propagated through the medium with a finite velocity equal to that of light. Accordingly we must consider the lines of electric strain as possessing inertia which, in fact, is the inertia in the medium in which the lines them-

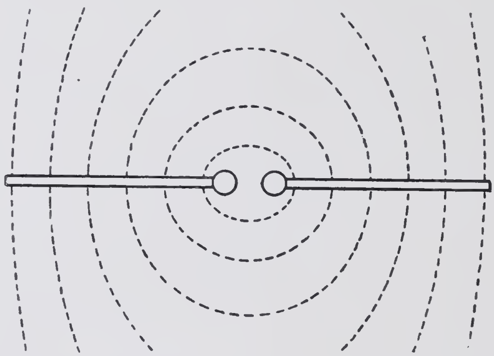


FIG. 12.—Lines of Electric Strain round a Hertz Linear Oscillator.

selves are a peculiar state. If the end of a line of electric strain has a sudden movement given to one end, this movement being in a direction at right angles to the direction of the line, the result is to create in the line a *kink* which travels outwards, just as would a *kink* on a stretched rope if the end were given a jerk at right angles to the direction of the rope. If the end of a line of electric force terminates on a point-charge of electricity or so-called electron, then a sudden movement of this electron, say from A to B (see Fig. 13), will be accompanied by the outward propagation of *kinks* or places of sudden bend or flexion along the lines of electric strain. It will be seen that we are here treating the lines of electric force as if they were objective realities and not merely curved or straight directions in space.

The question whether a line of electric force is to be regarded merely as a convenience of thought similar to a line of latitude or longitude, or whether it has an objective reality, is too large to discuss here fully. There are some good reasons for considering that in a

space occupied at least by air or other gas in which electric force exists, that force may not be distributed absolutely without discontinuity through the space, but the reader must be referred to Faraday's "Experimental Researches on Electricity," vol. iii., ser. xxix., §§ 3273, 3297, and 3299, and also to his memoirs "On Physical Lines of Magnetic Force," and "Thoughts on Ray Vibrations" (*Phil. Mag.*, ser. iii., vol. xxviii., 1846) for arguments in favour of this view. A confirmatory argument has been put forward by Sir J. J. Thomson in his book "Electricity and Matter," p. 63, for the physical existence or objective reality of lines of electric force based on the ionization of gases by Röntgen rays. The reader may also be referred to a suggestive article by the same author in the *Phil. Mag.*, ser. 6, vol. 19, p. 301, February, 1910, confirming this view of the field. It may therefore be taken that there are some valid reasons for thinking of lines of electric force as if they were discrete entities or bodies capable of being moved through space, or at least displaced in a continuous medium like vortex filaments in a liquid. These filaments behave as if they possessed inertia. In reality this inertia is the inertia of the medium in which they exist. When moved through space laterally these lines or tubes of electric force create magnetic force, this magnetic force being proportional to the velocity of the line of

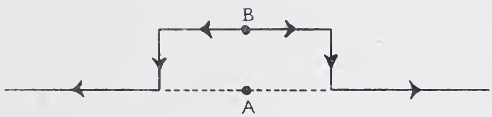


FIG. 13.

electric force perpendicular to itself. Since the lines or tubes possess inertia, a sudden displacement made at one place does not appear everywhere at once, but is propagated along the line of electric force as a kink in a rope travels along a rope.

Consider, then, a right angle kink travelling outwards along a line of electric strain. It moves with the velocity of light or with the velocity $u = \dfrac{1}{\sqrt{\mu K}}$.

The portion which constitutes the kink is therefore moving sideways or at right angles to its own direction through space. When a portion of a line of electric strain so moves through space it gives rise to a magnetic force at right angles to its own direction and to the direction in which it is moving. If a portion of a line of electric strain in a medium of dielectric constant k along which the electric force is E, moves with a velocity V in a direction at right angles to itself, it gives rise to a magnetic force $H = kEV$ at right angles to the electric force and to the direction of motion.

This is an important principle which must be clearly grasped. Suppose that a line of electric strain exists, which is represented by the firm line AB in Fig. 14, and that it moves parallel to itself from the position AB to the position CD. This movement may be considered to be produced by the creation of a closed line of electric strain of equal strength in the direction represented by the dotted

rectangle. If such a closed line is created, it would, so to speak, annihilate the strain line AB, because the circuital strain is in the opposing direction on that side, and would create a strain in the same direction along CD. This circuital strain is equivalent by Maxwell's principle to a closed electric current *whilst it is increasing*, and hence in coming into existence it must have a magnetic force, which in this case is towards the reader and perpendicular to the paper. Accordingly, during the time the movement of the original line of electric strain is taking place it is accompanied by the production of a magnetic flux, which is in a direction normal to itself and to its direction of motion. We can easily remember this directional relation by a *hand rule* as follows :—

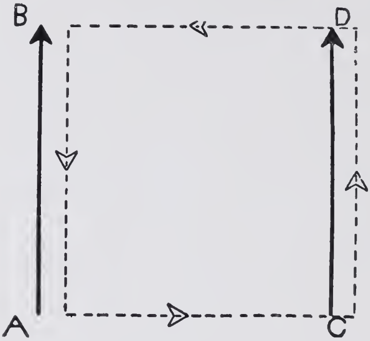


Fig. 14.—Lateral Displacement of a Line of Electric Strain, producing Magnetic Force at Right Angles.

Hold the forefinger, middle finger, and thumb of the *right hand* as nearly as possible in the direction of three co-ordinate axes mutually at right angles (see Fig. 15).

Let the direction of the *forefinger* represent that of the line of Electric *Force*, and the direction of the *thumb* the direction of its

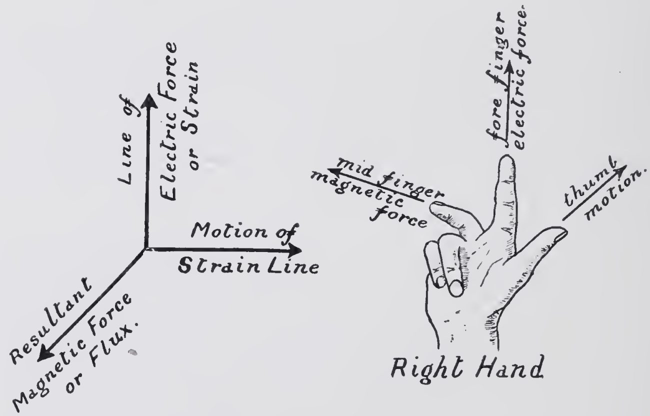


Fig. 15.—Mnemonic Rule for the Relation between Electric Strain, Motion of Strain Line, and Resulting Magnetic Force.

motion in space, then the direction of the *middle finger* will represent the direction of the resulting *Magnetic Flux*. If μ is the permeability of the medium, and V is the velocity of the line of electric strain perpendicular to itself, and if E is the electric force along the line, then the magnetic force H produced by its motion is such that

$H = \frac{E}{\mu V} = kVE$. The proof of this will be found in Oliver Heaviside's treatise on "Electromagnetic Theory," vol. 1, p. 56.

If, then, we consider a very long line in which electric oscillations are taking place, we can think of the electrons in the wire as oscillating backwards and forwards, and the lines of electric strain which abut perpendicularly on the wire as having their ends wagged backwards and forwards rapidly. The result is to propagate outwards along these lines right-angled kinks or discontinuities, as represented in Fig. 16, in which the dots represent the end-on view of the accompanying lines of magnetic force.

It will be seen that this is equivalent to the continual motion outwards from the wire of lines of electric strain which are parallel to the wire, these lines being made up of the union of the portions of the kinks which lie parallel to the wire and move outwards in a direction normal to their length.

It will be clear, then, that these moving electric strain lines give rise to magnetic force lines which must be distributed in circles round the wire with centres on its axis; and these also must be considered to expand outwards, like the ripples on a lake when a stone is thrown on its surface.

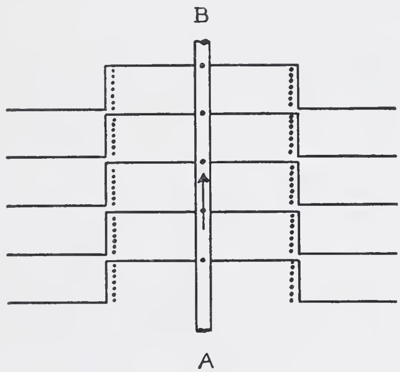


Fig. 16.

As the oscillations continue we have a procession of lines of electric strain in which the electric force is alternately directed one way and the other, which move outwards radially from the wire. Mingled with these, and at right angles to them, we have the circular lines of magnetic flux also alternately directed.

At any point in space not too near the wire there is an alternating electric force which is parallel to the wire in direction and an alternating magnetic force which is at right angles to it. The two forces are periodic and pulsate together, coming to their maximum values at the same instant at places not very near the wire. The result is to propagate outwards a cylindrical electromagnetic wave.

If the wire in which oscillations are taking place is finite in length, then the ends of the alternately directed electric strain lines will be united so as to form closed loops of electric strain which will move outwards in radial planes from the oscillator. We have then to find the form of the lines of strain and the magnitude of the forces at any point in the space round the oscillator.

We shall proceed then to discuss the effects produced when high frequency electric oscillations take place in a linear oscillator, such as that shown in Fig. 12. In a strikingly original paper Hertz considered mathematically the case of such oscillations produced in a pair of very short rods terminating in balls called a Hertz doublet,

or dumb-bell oscillator.[17] His analysis proceeds on the following lines.

We have seen that the components of the electric and magnetic forces, and hence all the quantities with which we are concerned in considering the changes of electric and magnetic force, propagated through the electromagnetic field must satisfy a certain differential equation of the type—

$$A^2\frac{d^2\phi}{dt^2} = \frac{d^2\phi}{dx^2} + \frac{d^2\phi}{dy^2} + \frac{d^2\phi}{dz^2} \quad . \quad . \quad . \quad . \quad . \quad (19)$$

or, as it may be written, $A^2\ddot{\phi} = \nabla(\phi)$, where ϕ is any function of x, y, z, and t, and A is the reciprocal of the velocity with which the effect is propagated through space (see equation (18), Chap. V. p. 350). This equation, as we have shown, is satisfied by the components of the electric and magnetic forces and potentials in the electromagnetic field.

We then consider a small Hertz oscillator or doublet, at the

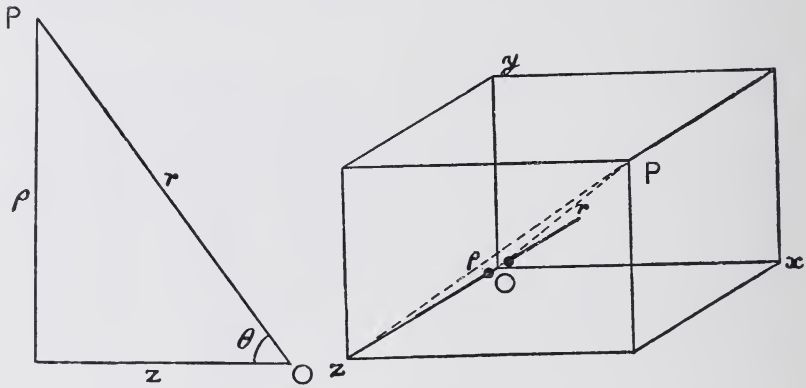


Fig. 17.

centre of which is a spark gap which is taken as the origin of co-ordinates. Let the doublet be placed horizontally, and its direction taken as the axis of z (see Fig. 17). Let the axis of x and the axis of y be taken in directions perpendicular to z, and in a plane perpendicular to the axis of the oscillator and at right angles to each other. Then the position P of any point in the field may be specified by stating its vertical distance ρ from the axis of z and its distance r from the origin. Everything being symmetrical with respect to the axis of z, the above system of co-ordination is sufficient.

Therefore $\rho = \sqrt{x^2 + y^2}$. Also we may define the position in polar co-ordinates where r is the distance of the point considered from the origin and θ is the angle between the directions of r and the z axis (see Fig. 17). Then $\rho = r \sin \theta$ and $z = r \cos \theta$. We desire to find

[17] See H. Hertz, *Wied. Annalen*, 1889, vol. 36, p. 1, "The Forces of Electric Oscillations treated according to Maxwell's Methods." See also "Electric Waves," by H. Hertz, English translation by D. E. Jones, p. 137.

expressions for the electric and magnetic force at all points in the field.

Suppose, then, that we consider the case of a small Hertzian oscillator consisting of two short metal rods placed in line with each other, the inner ends separated by a small spark gap and the outer ends terminated in small metal spheres. If we start oscillations in this linear circuit the balls will be alternately charged positively and negatively, and as these charges change in magnitude and sign an alternating current is produced in the rods.

To bring the problem within the grasp of simple analysis we must limit the conditions by assuming that the current in the rods has at all points the same value, and that the electric charges are located entirely on the balls. These assumptions are not completely in accordance with actual facts, but are not greatly in error when we are considering a short oscillator. We have, then, two effects produced in the surrounding space—

(i.) The electric charges on the spheres produce a distribution of electric force and *scalar electric potential* in the space; and

(ii.) The current in the rods produces a magnetic force and a *vector potential* in the space.

This term "vector potential" was a name given by Maxwell to a mathematical quantity such that its curl gives us the magnetic force at any point due to a current, just as the term "scalar potential" is the name for a quantity such that its space variation in any direction gives us the electrostatic force when the charges are steady. If we have any current i in an element of length of a circuit ds, then it can be shown that the vector potential due to this element at any point P at a distance r from the element is $\frac{ids}{r}$, and the vector potential due to any circuit is the vector sum of the vector potentials due to the several elements (see Fig. 18). The vector potential being a directed quantity can be resolved into axial components, and must be added according to the rules of vector addition. It is usual to denote the components of the vector potential in the directions of the axes of x, y, and z by the letters F, G, and H.

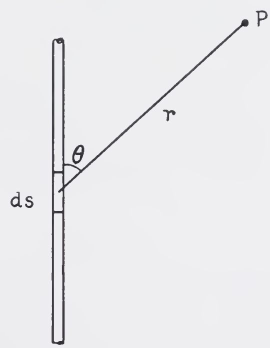


FIG. 18.

On the other hand, the scalar potential is not a directed quantity, and the scalar potential due to any distribution of electricity is the algebraic sum of that due to each element of charge dq separately. The scalar potential due to the charge dq at a point at a distance r being $\frac{dq}{r}$ and the total scalar potential being $\frac{\Sigma dq}{r}$. We shall denote the electric force at any point by E and its axial components by the letters X, Y, and Z as before, the scalar potential by ψ, and the axial components of the vector potential by F, G, and H, and the axial components of the magnetic force M by α, β, and γ. Then Maxwell showed that when we are considering operations in pure æther, for

which we may take the dielectric constant and permeability to be unity, we have the relations between the above quantities expressed by the six equations :—

$$\left.\begin{aligned} X &= -\frac{dF}{dt} - \frac{d\psi}{dx} \\ Y &= -\frac{dG}{dt} - \frac{d\psi}{dy} \\ Z &= -\frac{dH}{dt} - \frac{d\psi}{dz} \end{aligned}\right\} \quad . \quad (20) \qquad \left.\begin{aligned} \alpha &= \frac{dH}{dy} - \frac{dG}{dz} \\ \beta &= \frac{dF}{dz} - \frac{dH}{dx} \\ \gamma &= \frac{dG}{dx} - \frac{dF}{dy} \end{aligned}\right\} \quad . \quad . \quad (21)$$

These last being the expression of the fact that the magnetic force is the curl of the vector potential.

We have then to find for the small Hertzian oscillator in question expressions for the scalar and vector potential at all points around it. Since everything must be symmetrical with respect to the axis of the oscillator, it will be an advantage to assume the oscillator to be placed with its axis in the direction of the z-axis, and we shall, following Hertz, consider the y-axis to be drawn to the left, and the x-axis towards the reader. Everything is then symmetrical with respect to the axis of z, and we need only concern ourselves with the calculation of the forces in and at right angles to the plane yz.

Suppose, then, that a small sphere charged with a quantity of positive electricity $+q$ is placed at the origin O, and that we consider a point T of which the co-ordinates are y, z in the plane yz, and at a distance $\mathrm{OT} = r$ from the origin. The potential at the point due to this charge is $-\frac{q}{r}$. Suppose the sphere to be displaced along the z-axis in a positive direction by a distance $\frac{1}{2}\delta z$. The potential then created by it at the same point yz is—

$$-\left\{\frac{q}{r} + \frac{1}{2}\frac{d}{dz}\left(\frac{q}{r}\right)\delta z\right\}$$

Again, if an equal quantity of negative electricity $-q$ is placed on a small sphere at the origin, its potential at the point in question is $+\frac{q}{r}$, and if this is displaced downwards through a distance $\frac{1}{2}\delta z$, the potential due to it at the point T is—

$$-\left\{-\frac{q}{r} - \frac{1}{2}\frac{d}{dz}\left(-\frac{q}{r}\right)\delta z\right\}$$

If then we form a small oscillator of two spheres separated by a distance δz, and place the axis along the z-axis and the centre at the origin, then when the charges on the spheres are $+q$ on the top ball and $-q$ on the bottom ball, the scalar potential ψ due to these two electrostatic charges will be the sum of those due to each sphere separately, or will be—

$$\psi = -\frac{d}{dz}\left(\frac{q}{r}\right)\delta z \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

Suppose then that q varies with the time in a simple harmonic manner, so that $q = \text{Q} \sin nt$ where $\frac{2\pi}{n}$ is the periodic time of the oscillation, and let the product of the length of the oscillator and the maximum charge on each sphere $= \text{Q}\delta z = \phi$ be called the *electric moment* of the oscillator, then we have—

$$\psi = -\phi\frac{d}{dz}\left(\frac{\sin nt}{r}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

This expression, however, is obtained on the assumption that electric effects are propagated through space instantaneously. Hertz's experiments prove, however, that this is not the case, but that the forces and potentials are propagated with a finite velocity. Accordingly if the charges on the spheres of the oscillator are rapidly oscillating, the potential at any point in the field will not depend upon the state of the oscillator at the same instant, but upon a state at a time earlier by the time taken for the effect to be propagated the distance r. If, then, u denotes the velocity, the time taken by the effect to travel to the point in question is $\frac{r}{u}$.

Therefore the potential ψ at the selected point in the field is, in fact, given by—

$$\psi = -\phi\frac{d}{dz}\left(\frac{\sin n(t - \text{A}r)}{r}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

where $\text{A} = \frac{1}{u}$. Hence the effect is propagated as a wave motion. It is cyclical in space as well as in time. If we call λ the wave length or shortest distance between two places at which the effect is a maximum at the same instant, and T the periodic time, then $\lambda = u\text{T}$. It is convenient to write m for $\frac{2\pi}{\lambda}$ and $n = \frac{2\pi}{\text{T}}$. Also, since $\text{A}r$ is usually larger than t, we may write $\sin(mr - nt)$ instead of $\sin n(t - \text{A}r)$. It is convenient to write Π for $\frac{\sin(mr - nt)}{r}$.

We then have for the potential at the point yz, due to the oscillating electric charges of the oscillator, the expression—

$$\psi = -\phi\frac{d\Pi}{dz} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

We have, in the next place, to find the vector potential. At the moment when the charges on the spheres of the oscillator have a value q, the current along the connecting-rod has a value $-\frac{dq}{dt}$ in electrostatic measure, or $-\frac{1}{u}\frac{dq}{dt}$ in electromagnetic measure. Hence the vector potential due to this current existing in an oscillator of length δz at a point at a distance r from its centre is $\frac{1}{u}\frac{1}{r}\frac{dq}{dt}\delta z$.

Since r is independent of t, we can write the above expression in the form—

$$\frac{1}{u}\frac{d}{dt}\left(\frac{q}{r}\right)\delta z$$

and then, as in the case of the expression for the scalar potential, we must put instead of q the function Q sin $(nt - mr)$ to obtain the component H of the vector potential at the point in the field which is parallel to the direction of the current element. Finally, using the same notation as in the case of the scalar potential, we have—

$$\mathrm{H} = \frac{\phi}{u}\frac{d\Pi}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Since there is no current parallel to the axis of x or y, the components F and G of the vector potential are zero. Hence, inserting these values of ψ and H in the equations (25) and (26) for the electric and magnetic force components, we have—

$$\left.\begin{aligned} \mathrm{X} &= \phi\frac{d^2\Pi}{dxdz} \\ \mathrm{Y} &= \phi\frac{d^2\Pi}{dydz} \\ \mathrm{Z} &= -\phi\left(\frac{d^2\Pi}{dx^2} + \frac{d^2\Pi}{dy^2}\right) \end{aligned}\right\} \quad . \quad (27) \qquad \left.\begin{aligned} \alpha &= \mathrm{A}\phi\frac{d^2\Pi}{dydt} \\ \beta &= -\mathrm{A}\phi\frac{d^2\Pi}{dxdt} \\ \gamma &= 0 \end{aligned}\right\} \quad . \quad (28)$$

In these equations we assume that the dielectric constant and magnetic permeability are both taken as having unit value.

We have then to find the various differential coefficients of—

$$\Pi = \frac{\sin\,(mr - nt)}{r} = \frac{\sin\chi}{r}$$

and to introduce these into the above equations. We have then—

$$\left.\begin{aligned} \mathrm{X} &= \frac{\phi}{r^3}\left\{3\sin\chi - m^2r^2\sin\chi - 3mr\cos\chi\right\}\frac{x}{r}\frac{z}{r} \\ \mathrm{Y} &= \frac{\phi}{r^3}\left\{3\sin\chi - m^2r^2\sin\chi - 3mr\cos\chi\right\}\frac{y}{r}\frac{z}{r} \\ \mathrm{Z} &= \frac{\phi}{r^3}\left\{(2\sin\chi - 2mr\cos\chi) + \right. \\ &\qquad \left.(m^2r^2\sin\chi + 3mr\cos\chi - 3\sin\chi)\frac{y^2}{r^2}\right\} \end{aligned}\right\} \quad . \quad (29)$$

$$\left.\begin{aligned} \alpha &= \frac{\mathrm{A}\phi n}{r^2}\left\{mr\sin\chi + \cos\chi\right\}\frac{y}{r} \\ \beta &= -\frac{\mathrm{A}\phi n}{r^2}\left\{mr\sin\chi - \cos\chi\right\}\frac{x}{r} \\ \gamma &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

In the above equations the electric forces are expressed in electrostatic units, and the magnetic in electromagnetic units.

These equations show that the magnetic force is distributed in circles whose centres lie on the axis of z, because $a^2 + \beta^2$ is a constant, and $\frac{a}{y} + \frac{\beta}{x} = 0$. Hence there is no magnetic force along the line perpendicular to the axis z. If we write $\sin\theta$ for $\frac{y}{r}$ and $\cos\theta$ for $\frac{z}{r}$, and consider only the forces at points at a large distance from the origin in the plane yz, at which mr is therefore much greater than unity, and therefore m^2r^2 much greater than mr, we can reduce the above six equations, (29) and (30), to three, viz.—

$$\left.\begin{aligned} Y &= -\frac{\phi m^2}{r}\sin\chi\sin\theta\cos\theta \\ Z &= \frac{\phi m^2}{r}\sin\chi\sin^2\theta \\ a &= \frac{A\phi mn}{r}\sin\chi\sin\theta \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (31)$$

These last equations are those given by Hertz as his solution of the problem in his original memoir.[18] They show that at distances large compared with the dimensions of the oscillator the magnetic and electric forces vary inversely as the distance, a fact which has been approximately confirmed by experiment. Also since $\beta = Y = 0$ and $Z\cos\theta + Y\sin\theta = 0$, it is clear that at large distances the electric and magnetic forces are both perpendicular to the radius vector.

To obtain the equations to the lines of electric force, it is necessary to transform the above expressions for X, Y, and Z into another form. Let the distance of the point or space at which we are considering the force from the axis of z be denoted by ρ. Then $\rho^2 = x^2 + y^2$. Let us denote the component of the electric force in the direction of ρ by R. It is then quite easy to show by differentiation that—

$$\frac{d^2\Pi}{dx^2} + \frac{d^2\Pi}{dy^2} = \frac{1}{\rho}\frac{d}{d\rho}\left(\rho\frac{d\Pi}{d\rho}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

And hence we have—

$$Z = -\frac{\phi}{\rho}\frac{d}{d\rho}\left(\rho\frac{d\Pi}{d\rho}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Also $$R = P\frac{dx}{d\rho} + Q\frac{dy}{d\rho} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

And $$X = \phi\frac{d^2\Pi}{dxdz},\ Y = \phi\frac{d^2\Pi}{dydz} \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

It follows that—

$$R = \frac{\phi}{\rho}\frac{d}{dz}\left(\rho\frac{d\Pi}{d\rho}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

[18] See Hertz's book, "Electric Waves," English translation by D. E. Jones, "The Forces of Electric Oscillations treated according to Maxwell's Theories," Chap. IX., p. 137.

Now the equation to a line of electric force in the plane of ρ and z is $Zd\rho - Rdz = 0$; for this is the mathematical expression of the fact that the resultant force is directed along the line of force.

Substituting, then, in this last equation the values of Z and R given above, we have as the differential equation of the lines of electric force—

$$\frac{d}{d\rho}\left(\rho\frac{d\Pi}{d\rho}\right)d\rho + \frac{d}{dz}\left(\rho\frac{d\Pi}{d\rho}\right)dz = 0 \quad . \quad . \quad . \quad . \quad (37)$$

and integrating this last we have—

$$\rho\frac{d\Pi}{d\rho} = c = \text{a constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

as the equation to the lines of electric force of the oscillator in a meridional plane. If that plane is the plane yz, then we have $\rho = y$, and hence—

$$\rho\frac{d\Pi}{d\rho} = y\frac{d\Pi}{dy}$$

and the equation to the lines of force transposes into—

$$\cos(mr - nt) - \frac{\sin(mr - nt)}{mr} = \frac{c}{m\sin^2\theta} \quad . \quad . \quad . \quad (39)$$

we can then give to t any required value and determine a family of curves for a given epoch which represents the lines of electric force of the oscillator. If mr is a quantity large compared with unity, that is, if the field at a large distance from the oscillator is considered, then $\dfrac{\sin(mr - nt)}{mr}$ becomes a small quantity, and we may take as the equation to the lines of force—

$$\cos(mr - nt) = \frac{c}{m\sin^2\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

To plot the form of the lines we may then select any values of m, θ, and c such that $\dfrac{c}{m\sin^2\theta}$ is not greater than unity. We then find the angle a which has this fraction as their cosine, and it follows that—

$$mr = nt \pm a$$

Hence for every value of t and θ there are two values of r, except in the case when $\dfrac{c}{m\sin^2\theta} = 1$, when $a = 0$. This shows that the form of the line of electric force at a considerable distance from the oscillator is a closed curved loop, as shown in Fig. 19. If we take any fixed values of t, c, m, and θ, then a is determined. If then t increases, whilst c, m, and θ remain the same, there are still a pair of values of r derived from the equation $r = \dfrac{(nt + a)}{m}$, but their

absolute values are larger. Hence if we consider that any particular loop of force is identified by the particular value of the constant c, which is used to calculate the value of the angle α, whose cosine is $\frac{c}{m \sin^2 \theta}$, we may say that as time increases the loop moves outwards away from the oscillator. In a certain sense we may then say that the oscillations in the oscillator result in the throwing off of closed loops of electric force which move outwards away from the oscillator with the velocity of light. An objection has sometimes been raised to this mode of regarding the phenomenon, on the ground that we cannot identify or ear-mark any particular loop of electric force so as to follow its progress. If, however, we consider each particular loop as characterized by the constant c which belongs to it, we can, as it were, watch the movement of one particular loop. In the celebrated paper in which Hertz first discussed the theory of the oscillator on the lines above given, he gave a series of diagrams representing the distribution of the electric force, that is, the lines of electric force round such an oscillator or doublet when in action. He considered four stages separated in point of time by one-eighth part of a complete period T, or to $\frac{T}{8}$, and delineated the electric field at moments corresponding to $0, \frac{T}{8}, \frac{T}{4}, \frac{3T}{8}$, starting from the time when the current in the oscillator was a maximum.[19] These diagrams are not reproduced here, but they are very similar to those given in Figs. 1, 2, 3, 4, Plate VI. (see end of this chapter), which are taken from a paper by Dr. F. Hack. Hertz's diagrams are given in the English translation of his papers by D. E. Jones, entitled "Electric Waves," pp. 144, 145 (Macmillan and Co.).

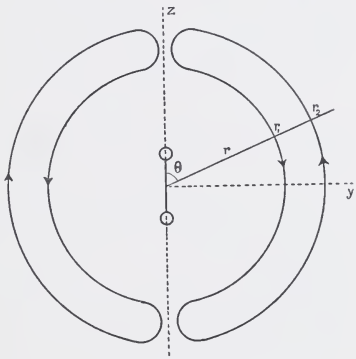


FIG. 19.

In Fig. 1, Plate VI., we see the oscillator is not a source of lines of electric force. The current in it is at its maximum value at that moment, and there are no electric charges at the ends of the rods.

In Figs. 2 and 3 we see the lines of electric force increasing as the charges accumulate, and the fourth diagram (Fig. 4) shows us the state of affairs as the discharge is beginning to take place. The

[19] In interpreting Hertz's diagrams, it must be remembered that his T is our $\frac{T}{2}$ and his λ is our $\frac{\lambda}{2}$. In the diagrams as drawn in Plate VI. the λ and T have the signification of a complete wave length and complete period. In Hertz's diagrams the lines of electric force are not continued right up to the oscillator, because the equations by which he determines their form are not valid at places very near the oscillator, but only at and beyond a certain distance, which is rather more than a quarter wave length.

lines of electric strain are bending inwards, and in one place a line has already crossed, or decussated, and formed a little detached loop or circle of electric strain. As this process continues the result is to detach or throw off closed loops of electric strain which are represented by the closed lines lying outside a certain boundary line. This boundary is the region within which the lines of strain are, as it were, giving birth to the closed loops, and it is only outside this area that we have electric radiation in the complete sense. Then, in addition to these lines of strain, we have to imagine other closed lines of magnetic flux which lie in planes perpendicular to the paper, and have their centres on the two axes or axis of the oscillator.

The result of the operations is then to detach from the oscillator a successive series of closed lines of electric strain, the strain being oppositely directed round successive loops. As these move outwards they are accompanied by expanding rings of magnetic flux in planes at right angles, and at a distance from the oscillator we have a spherical wave of electric radiation, the electric force everywhere being tangential to the surface, directed, so to speak, along lines of latitude, and magnetic flux directed along lines of longitude if we suppose the z axis to be the axis of the rotation of the earth. The magnetic flux and electric strain are periodic, or fluctuate harmonically in space and in time, but the magnetic flux is a maximum when the electric force is zero, and *vice versâ*. The energy is propagated outwards along radial lines, and therefore in a direction at right angles to the lines of electric and magnetic force.

At very great distances the spherical wave becomes practically a plane wave. The electric and magnetic forces are at right angles to each other, and in the plane of the wave. Along the line at right angles to the axis of the oscillator, the electric force is parallel to the axis of the oscillator, and the magnetic force is at right angles to it. The energy is transmitted at right angles to the electric and magnetic forces.

The reader should particularly notice that Hertz's and our assumption as to the form of the function which is represented by the symbol Π, viz.—

$$\Pi = \frac{\sin (mr - nt)}{r}$$

is equivalent to assuming that the electric oscillations in the radiator are persistent or *undamped*, in other words, are continuously maintained. We know, however, from Bjerknes' researches that this is very far from being the case, and that the oscillations of such a radiator are highly damped.

Accordingly, various investigators have considered the modification of the form of the magnetic and electric force lines when a train of highly damped oscillations is emitted. The effect of the damping has been considered in an important memoir by Professor K. Pearson and Miss A. Lee.[20]

[20] See Prof. Karl Pearson, F.R.S., and Miss Alice Lee, "On the Vibrations in the Field round a Theoretical Hertzian Oscillator," *Phil. Trans. Roy. Soc.*, 1900, vol. 193, A, p. 159.

Assuming that Π is a function of the form—

$$\frac{\mathrm{E}l}{r}\epsilon^{-p(t-\mathrm{A}r)}\,.\sin q(t-\mathrm{A}r) \quad . \quad . \quad . \quad . \quad . \qquad (41)$$

Professor Pearson and Miss Lee have discussed the whole question afresh in their above-mentioned paper, and draw the following general conclusion from their analysis :—

(I.) The effect of damping makes itself very sensible in modifying the form of the wave surface as propagated into space from a theoretical oscillator. The typical Hertzian wave diagrams require to be replaced by the fuller series shown in Plates II., III., IV., and V. at the end of this chapter.

(II.) *Three* waves of electromagnetic force may be considered as sent out from the oscillator, and these waves are capable of physical identification.

(i.) A component wave of transverse electric force.

(ii.) A component wave of electric force parallel to the axis.

(iii.) A wave of magnetic force.

The waves of magnetic force and of component axial electric force both move outwards with the same velocity at all points, and this velocity is identical for all points at the same distance from the oscillator. The intensity of the first force for points on the same sphere varies as the cosine of the latitude, but that of the second force is constant. The wave of component transverse electric force moves outward with equal velocity for all points at the same distance from the oscillator, and its amplitude varies as the cosine of the latitude. Its velocity after it has reached a certain distance from the origin is always greater than that of the waves of component axial electric force and of magnetic force, and its excess over the velocity of light tends to become three times the excess of the velocity of the wave of magnetic force over the velocity of light.

(III.) The velocities of these waves undergo remarkable changes in the neighbourhood of the oscillator, even within such distances as Hertz employed.

(IV.) The point of zero phase for both transverse and axial component electric waves does not coincide with the centre of the oscillator, so that these waves appear to start from a sphere of small but finite radius round the oscillator. A fourth wave, dealt with by Hertz, the wave of magnetic induction, does not, as he supposes, start from the centre of the oscillator with zero phase, but in the case of a damped wave train with a small but finite phase.

(V.) The analysis of these waves and of their singular points in the neighbourhood of the oscillator appears to add something to Hertz's discussion; it is possible that it may throw light on the difficulties which arise in connection with some of his interference experiments. It seems that all interference experiments ought to be made at distances greater than 6 to 7 from the centre of the oscillator, roughly about a wave length from the oscillator, whereas Hertz rather terminated than started his experiments at this distance. At such distances the phase curves are approximately parallel to their asymptotes. To exhibit the form of the electric strain lines at various epochs thrown off from a damped linear oscillator, Professor Pearson

and Miss Lee delineated a series of 56 diagrams (see Plates II., III., IV., and V.), covering a period of time equal to seven complete periods of the oscillator. The oscillator was assumed to be a small linear oscillator of such *moment* that the quantity $\frac{Q\lambda}{2\pi El}$ had values 50, 30, 10, 1, -1, -10, -30, -50. In the diagrams the oscillator is represented by the small dumb-bell within the inmost circle. The fine continuous curves correspond to the intensity $\pm$ 50, the fine dotted curves to the intensity $\pm$ 30, the heavy continuous curves to the intensity $\pm$ 10, and the heavy dotted curves to $\pm$ 1. The outermost circle is the boundary of the field explored, and the small inner circle surrounds the space within which it is not legitimate to consider the oscillator a double point. These curves show us the distribution on one meridional plane of the strain lines at various epochs. These diagrams of Professor Pearson and Miss Lee are very instructive. They show us the whole process of creating an electric wave. If the diagrams are cut out and placed round a zoetrope, or "wheel of life," the operation of a linear oscillator can be made visible to the eye. If reproduced on a film for a kinematograph they provide the means of showing an electric oscillator at work generating electric radiation.

In this paper it is assumed that the epoch from which the time is measured is that at which the vibrations begin, so that the field considered is confined within the sphere of which the radius is $\frac{t}{A}$, where A is the reciprocal of the radiation velocity.

Professor A. E. H. Love has pointed out in another interesting paper on this subject, that the front of the advancing wave is a surface of discontinuity in regard to the electric and magnetic forces.[21] Within this surface the forces are expressed by the formulæ given by Hertz, which may be generalized in the following form :—

$$\left.\begin{aligned} A\frac{\delta}{\delta t}(X, Y, Z) &= \text{curl }(\alpha, \beta, \gamma) \\ -A\frac{\delta}{\delta t}(\alpha, \beta, \gamma) &= \text{curl }(X, Y, Z) \end{aligned}\right\} \quad . \quad . \quad . \quad (42)$$

The only difference between these formulæ and those given by Hertz is that Hertz used a left-handed system of axes x, y, and z; and it is more convenient to employ the normal or right-handed system.

To adapt the analysis to the case of damped oscillations, Love, following Pearson and Lee, takes as the expression for Hertz's quantity Π the expression—

$$\Pi = \frac{C}{r}\epsilon^{-\frac{\delta}{\lambda}(ut-r)} \sin\frac{2\pi}{\lambda}(ut - r - \phi) \quad . \quad . \quad . \quad (43)$$

where C is a constant which determines the amplitude, δ is the logarithmic decrement of the oscillations per complete period, u is the velocity of radiation, and ϕ is a constant expressing the phase.

[21] See A. E. H. Love, "The Advancing Front of the Train of Waves emitted by a Theoretical Hertzian Oscillator," *Proc. Roy. Soc. Lond.*, 1904, vol. 74, p. 73.

According to the experiments of Bjerknes already quoted, δ (for one complete period) has a value of about 0·4 for an oscillator sending out waves 10 metres in length.

If we put $\delta = 0$ and $\phi = 0$ in the last expression for Π, it reduces to that used by Hertz.

Love has delineated (*loc. cit.*) the form of the lines of electric force round a Hertz doublet or ideal dumb-bell oscillator in action, taking into account the discontinuity which exists at the surface of the wave front. These diagrams (see Plate V.) are modifications of those given by Pearson and Lee. In these diagrams four lines of electric force are drawn for different epochs, which are respectively denoted by heavy firm, heavy dotted, light firm, and light dotted lines.

The diagrams given in Figs. 4–11, Plate V., represent, according to Professor Love, the state of the electric field within and without the wave front surface at various epochs, and these, he says, should replace the diagrams 4–11 given in Plate II. by Professor Pearson and Miss Lee. They have only been commenced on the outside of a small sphere drawn round the oscillator. The lines above mentioned have been drawn in Love's diagrams corresponding to values of $\frac{Q\lambda}{2\pi El}$ in Hertz's notation, equal respectively to $\pm 0{\cdot}01$, $\pm 0{\cdot}1$, $\pm 0{\cdot}3$, $\pm 0{\cdot}5$. The fine continuous circular line enclosing the oscillator is a surface for which $Q = 0$, or the electric force has no radial component.

These diagrams show in a striking manner the discontinuity in the direction of the lines of electric force at the wave front surface represented by the fine continuous circle. Before the discharge begins we must regard the electric force lines as stretching out to infinity in all directions, and when the discharge happens, a discontinuity or kink in these lines flies outwards through space with the velocity of light. The diagrams show also the gradual formation and detachment from the oscillator of the closed loops of electric force, and their enlargement and the formation of others within them.

There are many points of interest involved in the examination of the force of the field near to, or in the direction of, the axis of a small oscillator to which space cannot here be given. From the point of view of radiotelegraphy we are not much concerned with the field in close proximity to the oscillator, but the reader may be referred for an exposition of some of them to a "Treatise on Magnetism and Electricity," by Andrew Gray, vol. i. p. 400, where a discussion is given of the field of the oscillator at various points near to it.

8. **Poynting's Theorem.**—We owe to Dr. J. H. Poynting an important theorem concerning the energy transmission through the electromagnetic field.[22] If a small volume is marked off by a closed surface in the field, and the energy of electric strain and magnetic flux contained in it be varying, Poynting proved that the amount of energy which enters each element of the surface is measured by the sum of the product of the electric and magnetic forces resolved along

[22] See Prof. J. H. Poynting, F.R.S., *Phil. Trans. Roy. Soc.*, 1884, part ii. p. 343, "On the Transfer of Energy in the Electromagnetic Field."

each element of the surface, multiplied by the sine of the angle between their directions and divided by 4π.

Maxwell had previously shown that the energy of the electromagnetic field is made up of two parts, due respectively to the electric strain and to the magnetic flux. The part due to the electric strain is equal, per unit of volume, to $\frac{K}{8\pi} \cdot \mathsf{E}^2$, where E is the electric force assumed constant throughout the unit of volume, and K is the dielectric constant.[23]

If we consider any finite space throughout which there is a disposition of electric force, E, and if the rectangular components of that force at any point are X, Y, and Z, then, to obtain the whole electrostatic energy contained in the given volume, we have to find the value of the integral—

$$\frac{K}{8\pi}\int (X^2 + Y^2 + Z^2)dv \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

where dv is an element of volume.

This expression follows at once from the fact that if D is a displacement produced by an electric force, E, in the same direction, the two being uniform throughout the space of a unit of volume, then the energy of strain per unit of volume (T_s) is equal to half the product of the force and the displacement.

$$\text{But } D = \frac{K}{4\pi}\mathsf{E}, \text{ hence } T_s = \frac{K}{8\pi}\mathsf{E}^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

Again, Maxwell shows that another part of the energy of the field is magnetic, and that if H is the uniform magnetic force throughout a unit of volume, the magnetic energy (T_m) contained therein is equal to $\frac{\mu}{8\pi}\mathsf{H}^2$. Hence, to obtain the magnetic energy contained in any finite space, we have to find the value of the integral—

$$\frac{\mu}{8\pi}\int (\alpha^2 + \beta^2 + \gamma^2)dv \quad . \quad . \quad . \quad . \quad . \quad . \quad (46)$$

where dv is a unit of volume, and μ is the magnetic permeability of the material filling it.

Accordingly, in the æther, where Hertz takes $\mu = 1$ and $K = 1$, the total energy stored up in any volume is the sum of the two energies given by the two expressions, viz.—

$$\text{(1) The electrostatic energy} = \frac{1}{8\pi}\int (X^2 + Y^2 + Z^2)dv \quad . \quad . \quad (47)$$

$$\text{(2) The magnetic energy} = \frac{1}{8\pi}\int (\alpha^2 + \beta^2 + \gamma^2)dv \quad . \quad . \quad . \quad (48)$$

Starting from these expressions, and considering a reduced case, we may follow the method which Hertz employed in proving the theorem due to Poynting.

[23] See Maxwell's "Electricity and Magnetism," vol. ii. p. 253, § 638.

We take the fundamental equations connecting the electric and magnetic forces in the electromagnetic field, viz.—

$$(1)\left\{\begin{aligned} A\frac{d\alpha}{dt} &= \frac{dZ}{dy} - \frac{dY}{dz} \\ A\frac{d\beta}{dt} &= \frac{dX}{dz} - \frac{dZ}{dx} \\ A\frac{d\gamma}{dt} &= \frac{dY}{dx} - \frac{dX}{dy} \end{aligned}\right. \qquad (2)\left\{\begin{aligned} A\frac{dX}{dt} &= \frac{d\beta}{dz} - \frac{d\gamma}{dy} \\ A\frac{dY}{dt} &= \frac{d\gamma}{dx} - \frac{d\alpha}{dz} \\ A\frac{dZ}{dt} &= \frac{d\alpha}{dy} - \frac{d\beta}{dx} \end{aligned}\right. \qquad (49)$$

In these equations X, Y, and Z represent the rectangular components of the electric force in electrostatic units, and α, β, and γ the rectangular components of the magnetic force, and $A = \frac{1}{u}$ is the reciprocal of the electromagnetic velocity.

Multiply equations (1) by α, β, and γ, and equations (2) by X, Y, and Z, respectively, and add the results. Then multiply each side by an element of volume $dx \,.\, dy \,.\, dz$, and integrate, and we arrive at the equation—

$$\begin{aligned} &A\iiint\left(\alpha\frac{d\alpha}{dt} + \beta\frac{d\beta}{dt} + \gamma\frac{d\gamma}{dt}\right)dx\,.\,dy\,.\,dz \\ &\qquad\qquad + A\iiint\left(X\frac{dX}{dt} + Y\frac{dY}{dt} + Z\frac{dZ}{dt}\right)dx\,.\,dy\,.\,dz \\ &= \iiint\frac{d}{dx}(\gamma Y - \beta Z)dx\,.\,dy\,.\,dz + \iiint\frac{d}{dy}(\alpha Z - \gamma X)dx\,.\,dy\,.\,dz \\ &\qquad\qquad + \iiint\frac{d}{dz}(\gamma X - \alpha Y)dx\,.\,dy\,.\,dz \\ &= \iint(\gamma Y - \beta Z)dy\,.\,dz + \iint(\alpha Z - \gamma X)dx\,.\,dz \\ &\qquad\qquad + \iint(\beta X - \alpha Y)dx\,.\,dy \quad . \quad . \quad . \quad . \quad (50) \end{aligned}$$

Let dS be an element of the surface of the element of volume, and let l, m, and n be its direction cosines. Then, by a well-known theorem in solid geometry—

$$ld\text{S} = dy\,.\,dz, \qquad md\text{S} = dx\,.\,dy, \qquad md\text{S} = dx\,.\,dy \quad . \quad (51)$$

This simply amounts to saying that the projection of the element of volume $dx\,.\,dy\,.\,dz$ on the three co-ordinate planes gives us three surfaces, having respectively areas equal to $dy\,.\,dz$, $dx\,.\,dz$, $dx\,.\,dz$, respectively.

Again, in order to interpret the above equation we must remind the reader of a simple theorem in geometry of three dimensions. If any plane area dS is projected on the three co-ordinate planes, we have as above—

$$ld\text{S} = \text{S}_1, \qquad md\text{S} = \text{S}_2, \qquad nd\text{S} = \text{S}_3,$$

where S_1, S_2, and S_3 are the projections on the planes of reference, and l, m, and n the direction cosines of the normal to the surface. If we

multiply each of these last expressions by l, m, and n respectively, and remember that $l^2 + m^2 + n^2 = 1$, we have—

$$dS = lS_1 + mS_2 + nS_3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (52)$$

Consider now the lines meeting at the origin (see Fig. 20), one of which represents the electric force **E** in the field with its three axial components X, Y, and Z, and the other one represents the magnetic force **H** with components α, β, and γ. Joining the outer extremities of lines **E** and **H**, we have a triangle OEH, of which the area is $\frac{1}{2}$**EH** sin ϕ, where ϕ is the angle between the lines OE, OH. If we project this triangle on the three co-ordinate planes, it is not difficult to show that on the yz plane this projected area OE′H′ is equal to the difference between a triangle whose area is $\frac{1}{2}\beta\gamma$, and the sum of two other areas $\frac{1}{2}(\beta + Y)(\gamma - Z)$ and $\frac{1}{2}YZ$. Hence the area of the projection of $\frac{1}{2}$**EH** sin ϕ on the yz plane is $\frac{1}{2}YZ + \frac{1}{2}(\beta + Y)(\gamma - Z) - \frac{1}{2}\beta\gamma = \frac{1}{2}(\gamma Y - \beta Z)$. In the same manner we can show that the projections on the two other planes xz and xy are $\frac{1}{2}(\alpha Z - \gamma X)$ and $\frac{1}{2}(\beta X - \alpha Y)$. Hence, by the theorem just mentioned, we have—

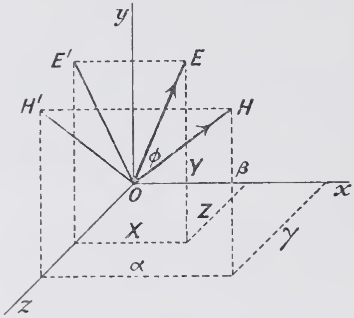


FIG. 20.– Diagram illustrating Poynting's Theorem.

$$\mathbf{EH} \sin \phi = (\gamma Y - \beta Z)l + (\alpha Z - \gamma X)m + (\beta X - \alpha Y)n$$

where l, m, and n are the direction cosines of the normal to the triangle OEH. Returning then to the equation (50), we can write it in the following form. Since—

$$\alpha\frac{d\alpha}{dt} + \beta\frac{d\beta}{dt} + \gamma\frac{d\gamma}{dt} = \frac{1}{2}\frac{d}{dt}(\alpha^2 + \beta^2 + \gamma^2) = \frac{d}{dt}(\tfrac{1}{2}\mathbf{H}^2) \quad . \quad (53)$$

and $$X\frac{dX}{dt} + Y\frac{dY}{dt} + Z\frac{dZ}{dt} = \frac{1}{2}\frac{d}{dt}(X^2 + Y^2 + Z^2) = \frac{d}{dt}(\tfrac{1}{2}\mathbf{E}^2) \quad . \quad (54)$$

we can write the left-hand side of (50) in the form [24]—

$$4\pi A\frac{d}{dt}\iiint\left(\frac{\mathbf{E}^2 + \mathbf{H}^2}{8\pi}\right)dv$$

where dv is an element of volume, and by the theorems just stated the right-hand side of (50) can be written—

$$\iint(\mathbf{EH} \sin \phi)dS \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

where dS is an element of surface and **E** and **H** are the electric

[24] The factor A, which is the reciprocal of u, the electromagnetic velocity comes in here because Hertz supposes that the electric force is measured in electrostatic units.

and magnetic forces resolved along it. Hence, dividing $4\pi A$, we have—

$$\frac{d}{dt}\iiint\left(\frac{\mathsf{E}^2+\mathsf{H}^2}{8\pi}\right)dv=\frac{1}{4\pi A}\iint(\mathsf{EH}\sin\phi)dS$$

The interpretation of the above equation is as follows: It tells us that the rate at which the total electromagnetic energy in any space is changing with time is measured by the sum or integral of the products of the electric and magnetic forces resolved along each element of surface of the volume multiplied by the sine of the angle between the directions of these resolved parts, and divided by $4\pi A$. As, therefore, the right-hand expression is a surface integral, it implies that the energy enters or leaves the interior of the space by passing inwards or outwards through the bounding surface.

This remarkable theorem is consistent with the law of conservation of energy, which asserts that if the energy in any region is increased or diminished it is not due to the creation or annihilation of energy, but to the arrival or departure of energy in some form which must come in through the surface.

9. Radiation from an Oscillator.—Hertz applied Poynting's theorem to calculate the radiation of energy from an electric oscillator or doublet when in action.

Describe round the oscillator a sphere of radius r, where r is large compared with the wave length, and apply Poynting's theorem to this sphere. Take any point on the surface of this sphere. Then the polar co-ordinates of this point are r and θ, the angle θ being measured from the axis of the oscillator.

At the point so defined the electric force resolved tangentially to the spherical surface is $Z\sin\theta - Y\cos\theta$, and the magnetic force at right angles to this is the component α. If we substitute for Z, Y, and α the values already formed in equations (31), we have for the product $\mathsf{EH}\sin\phi$ the quantity $\frac{A\phi^2m^3n}{r^2}\sin^2\chi\sin^2\theta$, since $\sin\phi = 1$. The element of area of the sphere may be taken to be the zone of area $2\pi r^2\sin\theta\, d\theta = dS$ lying between small circles of polar distance θ and $\theta + d\theta$, and of mean radius $r\sin\theta$.

Accordingly, the whole energy sent out in a time dt through this zone is equal to $\frac{1}{4\pi A}(\mathsf{EH}\sin\phi)dS$, which by substitution of the above values is found to be—

$$\frac{\phi^2m^3n}{2}\sin^2\chi\sin^3\theta\, d\theta dt \quad . \quad . \quad . \quad . \quad . \quad (56)$$

Hence the whole energy escaping through the whole sphere *per half period* is obtained by taking the integral of the above quantity between the limits 0 and π, and 0 and T. The reader should again note that Hertz uses the symbol T for the half period, and λ, therefore, for the half wave length.

The integral—

$$\int\sin^3\theta\, d\theta=\int\sin\theta\, d\theta-\int\cos^2\theta\sin\theta\, d\theta=\tfrac{1}{3}\cos^3\theta-\cos\theta$$

Hence we have $\int_0^\pi \sin^3\theta\, d\theta = \frac{4}{3}$

Also $\int \sin^2(mr - nt)dt = \int \frac{dt}{2} - \frac{1}{2}\int \cos 2(mr - nt)dt$

$$= \frac{t}{2} + \frac{1}{2}\frac{\sin 2(mr - nt)}{2n}$$

Now, $m\lambda = nT$. Hence $(mr - nT) = m(r - \lambda)$, and since by supposition r is large compared with λ, we have $(mr - nT) = mr$.

Therefore $\int_0^T \sin^2(mr - nt)dt = \frac{T}{2}$

Collecting these results, we find that the whole energy sent out through the sphere per half period is given by—

$$\frac{4\phi^2 m^3 nT}{12} = \frac{\phi^2 m^3 nT}{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

But $m\lambda = nT$ and $m = \frac{\pi}{\lambda}$ according to Hertz's notation

Therefore the whole energy sent out per half period is given by the expression—

$$\frac{\phi^2\pi^4}{3\lambda^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (58)$$

If, however, we remember that Hertz uses λ for the *half wave length*, we may change the formula into our usual notation by writing $\frac{\lambda}{2}$ instead of λ, and we then have—

$$\left.\begin{array}{l}\textit{The energy sent out by the oscillator}\\ \quad\textit{per half period}\end{array}\right\} = \frac{8\phi^2\pi^4}{3\lambda^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (59)$$

or

$$\left.\begin{array}{l}\textit{The energy sent out by the oscillator}\\ \quad\textit{per complete period}\end{array}\right\} = \frac{16\phi^2\pi^4}{3\lambda^3} \quad . \quad . \quad . \quad . \quad (60)$$

where λ has the ordinary signification of the complete wave length.

This is the formula (30) we have used in § 8 of Chap. III. We shall now apply this result to calculate the energy sent out per half period by the Hertz oscillator, described in § 8 of Chap. III. We have there seen that an oscillator described by Hertz was of such dimensions that each half had with reference to the other a capacity of 10 cms. Also, he employed a spark gap 1 cm. in length, which corresponds to a spark potential of 30,000 volts, or 100 C.G.S. electrostatic units. Hence the charge E on each half of the oscillator was 1000 electrostatic units. The length l was 100 cms., and the wave length λ was 480 cms. Also, $\pi^4 = 97{\cdot}4$.

Therefore the energy sent out per half period is—

$$\frac{8 \times 97{\cdot}4 \times (1000)^2 \times (100)^2}{3 \times (480)^3} = 23{,}636 \text{ ergs (nearly)}$$

But the energy imparted to the oscillator at starting was equal to $\frac{1}{2} \times 10 \times (100)^2 = 50{,}000$ ergs. Hence, we see that in about two half oscillations, or one complete period, the energy is dissipated. The frequency of the oscillator is nearly 50×10^6 (see § 8, Chap. III., p. 243). Hence the half period occupies 10^{-8} of a second, and the radiation of the energy is 23×10^{11} ergs per second. Hence, to maintain this radiation continuously would necessitate the expenditure of 300 horse-power. It will be seen, therefore, that even a small oscillator might require to be supplied with an immense power to keep its electric radiation going continuously.

We may apply the above equation (60) to calculate the radiation from another oscillator which will be useful later on (see Chap. VIII. § 9).

We may put the equation (60) first into a form more useful for calculation. If C is the capacity in microfarads of each sphere or half of the oscillator with respect to the other, and V is the maximum P.D. in volts before discharge, then $\frac{C \times 9 \times 10^5 \times V}{300}$ is the maximum charge of the oscillator in electrostatic units. Hence, if l is the length of the rod in centimetres we have $3000\, CVl = \phi$ as the maximum electric moment in electrostatic units. Accordingly the radiation per period is given by—

$$W = \frac{17}{10^{23}} C^2V^2l^2N^3 \text{ ergs}$$

C being the capacity in microfarads, V the P.D. in volts, l the length in centimetres, and N the frequency.

The radiation per period for a Hertzian oscillator increases, therefore, as the cube of the frequency and as the square of the potential just before discharge.

For a given oscillator the initial energy imparted to it is—

$$\frac{CV^2}{2 \times 10^6} \times 10^7 = 5CV^2 \text{ ergs}$$

and from this and the previous expression for the energy radiated per period we can tell how many oscillations take place in a train.

Suppose a large Hertzian oscillator is constructed by taking two rods each 2 metres long and attaching to one end of each rod a spark ball and to the other a disc of metal 1 metre in diameter. These, when placed in line, give us an oscillator in which oscillations can be set up in the Hertzian manner. The capacity of a circular disc is $\frac{d}{\pi}$ electrostatic (E.S.) units, where d is the diameter in centimetres. Hence the capacity of each disc of the above oscillator with respect to the other is—

$$\frac{100}{2\pi} = \frac{100}{6{\cdot}28} = 15 \text{ E.S. units}$$

or—

$$\frac{15}{9 \times 10^5} = \frac{1}{60{,}000} \text{ mfd.}$$

Let the connecting rod be 0·5 cm. diameter. Now the inductance in centimetres L of a straight rod of length l and diameter d_1 is—

$$L = 2l\left(\log_\epsilon \frac{4l}{d_1} - 1\right)$$

and for the above rod is 800 (8·05 − 1) = 5640 cms. Hence for the above oscillator the oscillation constant $\sqrt{CL} = 0·3$ nearly, and the frequency N of the oscillation is—

$$\frac{5·033 \times 10^6}{\sqrt{CL}} = 17 \times 10^6 \text{ (nearly)}$$

The wave length λ of the fundamental wave is 1760 cms. Suppose, then, that the spark gap of the oscillator is 1 cm., then the spark potential V corresponding to this is 30,000 volts, or 100 E.S. units, and the radiation in ergs per period is given by—

$$W = \frac{17}{10^{23}} C^2V^2l^2N^3 = \frac{17}{10^{23}} \frac{9 \times 10^8 \times 16 \times 10^4 \times (17)^3 \times 10^{18}}{36 \times 10^8}$$

$$= \frac{17 \times 9 \times 16 \times (17)^3}{36 \times 10} = 33{,}410 \text{ ergs}$$

Hence this oscillator radiates nearly 33,000 ergs per period. The original charge of energy is—

$$\frac{1}{2}CV^2 = \frac{9 \times 10^8 \times 10^7}{2 \times 6 \times 10^{10}} \text{ ergs} = 75{,}000 \text{ ergs}$$

Accordingly the initial energy is all radiated in about two complete periods.

Suppose, however, we were to maintain this rate of radiation by creating in the oscillator persistent oscillations, the rate of radiation would be 56·1 kw., or nearly 75 horse-power.

This example shows us the enormous radiative power of open or Hertzian oscillators.

One more point in connection with them is of considerable interest.

Let the maximum value of the current reckoned in amperes in the centre of the antenna be denoted by a and its electrostatic measure by I. Then—

$$\frac{a}{10} = \frac{1}{u} \text{ and } I = CV2\pi N$$

Accordingly we may transform the expression for the energy W radiated in ergs per period as follows:—

$$W = \frac{16\pi^4 \cdot C^2V^2l^2}{3\lambda^3} = \frac{16\pi^4 a^2 u^2 l^2}{3\lambda^3 100 \cdot 4\pi^2 N^2} = \frac{4\pi^2}{300} \cdot \frac{l^2}{\lambda^2} \frac{u}{N} a^2$$

If the oscillations are continuous and of frequency N, then, since $\pi^2 = 9·87$ or nearly 10, the power in watts radiated is given by—

$$P = 394·8 \frac{l^2 a^2}{\lambda^2}$$

Approximately we can say that the radiation from such an oscillator reckoned in ergs per period is given by the expression—

$$W = \frac{2}{15}\frac{l^2a^2}{\lambda} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

If we suppose a sphere described round the oscillator of radius r large compared with the dimensions of the oscillator, then the surface of this sphere is $4\pi r^2$, and the mean density of the radiation in ergs per square cm. is—

$$\frac{W}{4\pi r^2} = \frac{1}{30}\frac{la^2}{\pi r^2}\frac{l}{\lambda}$$

10. Connection between the Logarithmic Decrement and the Radiation of an Oscillator.—We can establish a connection between the expression as above obtained by Hertz for the radiation of energy per period from an oscillator and the radiation logarithmic decrement, and thus obtain a means of predetermining the value of the radiation decrement. For since the radiation in ergs per complete period is given by the expression—

$$W = \frac{16\pi^4\phi^2}{3\lambda^3}$$

it follows that the rate of radiation of energy, which we may denote by $\frac{dW}{dt}$, is given by—

$$\frac{dW}{dt} = \frac{16\pi^4\phi^2}{3\lambda^3 T} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (62)$$

But $\phi = Ql$, where Q is the maximum charge on each sphere of the oscillator, and l is its length or the distance between the spheres, and the original energy of the oscillator W is equal to $\frac{E^2}{2C}$, where C is the capacity of one half of the oscillator with respect to the other half. If we consider the oscillator as consisting of two spheres, each of radius R, and neglect the capacity of the short rods between the spheres and the spark balls, then the capacity of each sphere is equal to R electrostatic units, and the capacity of one half of the oscillator with respect to the other is $\frac{R}{2}$. Hence $C = \frac{R}{2}$, and $W = \frac{E^2}{R}$. Therefore—

$$\frac{dW}{dt} = \frac{16\pi^4 l^2 RW}{3\lambda^3 T} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (63)$$

$$\text{or} \quad \frac{dW}{W} = \frac{16\pi^4 l^2 Ru}{3\lambda^4}dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (64)$$

$$\text{Accordingly} \quad W = \epsilon^{-ht}W_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

where W_0 is the original charge of energy, and—

$$h = \frac{16\pi^4 l^2 Ru}{3\lambda^4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

u being the velocity of radiation, and $uT = \lambda$. Therefore the time t in which the energy of the oscillator falls to $\frac{1}{\epsilon}$ of its original value is given by $t = \frac{1}{h}$, and the time in which the amplitude of the oscillations falls to $\frac{1}{\epsilon}$ of the original amplitude is given by $t = \frac{2}{h}$.

If we then define the logarithmic decrement, as we have done, to be the logarithm of the ratio of two successive oscillations in opposite directions or separated by half a complete period, and if we call I_1 and I_m the first and the mth oscillations respectively, we have—

$$I_m = I_1 \epsilon^{-(m-1)\delta}$$

$$\text{and hence} \quad I_m^2 = I_1^2 \epsilon^{-2(m-1)\delta}$$

where δ is the log. dec. is defined as above.

The energy of an oscillation varies as the square of the amplitude, and accordingly the time t in which the energy falls to $\frac{1}{\epsilon}$ of its initial value is such that—

$$2(m = 1) = \frac{1}{\delta}, \text{ but } (m-1)\frac{T}{2} = t$$

$$\text{Therefore} \quad \frac{T}{4\delta} = \frac{1}{h} \text{ or } \delta = \frac{hT}{4}$$

But we have found (see equation 66) that—

$$h = \frac{16\pi^4 l^2 \mathrm{R} u}{3\lambda^4}$$

$$\text{Hence} \quad \delta = \frac{16\pi^4 l^2 \mathrm{R}}{12\lambda^3} \quad \ldots\ldots\ldots\ldots \quad (67)$$

$$\text{or} \quad \delta = \frac{16\pi^4 l^2 \mathrm{C}}{6\lambda^3} \quad \ldots\ldots\ldots\ldots \quad (68)$$

where C is the capacity of one part of the oscillator with respect to the other.

This last expression gives us a value for the radiation decrement δ_r in terms of the quantities l, C, and λ. The time τ in which the amplitude of the oscillation falls to $\frac{1}{\epsilon}$ of its original is twice that in which the energy falls to $\frac{1}{\epsilon}$ of its original value, and is therefore equal to $\frac{2}{h}$ or to $\frac{T}{2\delta}$. Hence the time τ in which the *amplitude* of the oscillations falls to $\frac{1}{\epsilon}$ of its original value is given by—

$$\tau = \frac{T}{2\delta} = \frac{6\lambda^3 T}{32\pi^4 l^2 \mathrm{C}} = \frac{6\lambda^3}{16\pi^4 l^2 \mathrm{R}} T \quad \ldots\ldots \quad (69)$$

since $\mathrm{C} = \frac{\mathrm{R}}{2}$.

Thus in the case of the Hertz oscillator already mentioned, consisting of two spheres, each 15 cms. radius, placed at the ends of a rod 100 cms. in length with spark gap in the centre, Hertz found by experiment that this radiator emitted a wave having a wave length of 560 cms. Hence $\lambda = 560$ cms., and—

$$\tau = \frac{6 \times (560)^3 \times T}{16 \times 97{\cdot}4 \times (100)^2 \times 15} = 4{\cdot}47T \quad . \quad . \quad . \quad (70)$$

For an oscillator of nearly equal size, Bjerknes found experimentally $\tau = 3{\cdot}8T$.

11. Radiation of Electromagnetic Waves from a Marconi Earthed Oscillator.—G. Marconi made a remarkable improvement in the practical means for the production of electric waves by his invention of the earthed vertical oscillator (see Chap. VII.). Although Hertz had employed oscillators as above described, both in horizontal and vertical positions, it had not occurred to any one before the time when Marconi began to experiment on this subject to bury a Hertz radiator partly in the earth with its axis vertical.

Marconi did that which was equivalent to this when he connected an insulated elevated cylinder or plate suspended in the air by a wire, with one spark ball attached to the secondary circuit of an induction coil, and connected the other spark ball to a plate buried in the earth, On bringing the spark balls near together and starting the coil in action, we set in operation an oscillator, one half of which is buried in the earth. By so doing an oscillator is constructed which is equivalent or nearly so in radiative power to a complete or Hertzian oscillator of double the total length. The novelty of such a suggestion is to be measured rather by its non-obviousness to experts than by the simplicity of the device in itself, and its value is proved by its utility.

Since the earth is a fairly good conductor, we may consider the insulated aerial wire to form with the earth, and the space in between, a condenser. The aerial wire has a certain capacity with respect to the earth. Hence, when the aerial is charged with electricity, there must be lines of electric strain stretching from it to the earth, in all directions around it symmetrically, as shown roughly in Fig. 21. If we now consider the aerial to be suddenly discharged across the spark gap, we may, in accordance with principles already explained, consider that the ends of the lines of strain terminate on electrons in the aerial, and these electrons will receive a sudden displacement or be set in oscillation. Hence, in accordance with the explanation already given in § 7, the inertia quality of the lines of electric force will come into play, and kinks or displacements be propagated along them. These kinks or discontinuities unite into loops of electric

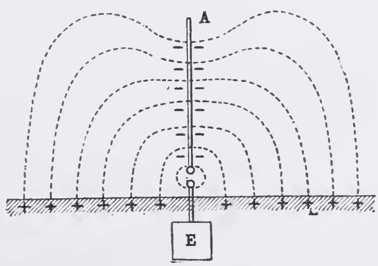


Fig. 21.—Rough Representation of Lines of Electric Strain round a Simple Marconi Antenna before Spark Discharge.

force, which are detached from the antenna. In the case, however, of the Marconi aerial, these loops must be semi-loops, with their feet or ends resting on the earth. As each loop is formed it is pushed outwards by others, and the process may be diagrammatically indicated as in Figs. 22 and 23. Accompanying this outward movement of the semi-loops of electric strain, there will be an expansion of circular

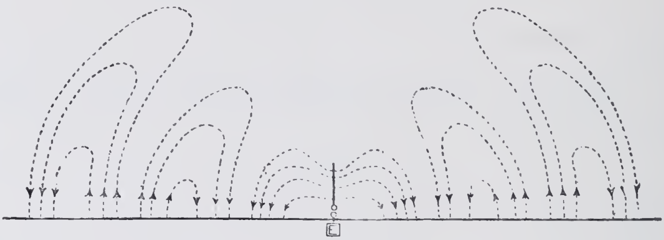


Fig. 22.—Diagrammatic Representation of the Detachment of Semi-loops of Electric Strain from a Simple Marconi Antenna or Rod Oscillator.

lines of magnetic flux in circles with their planes parallel to the earth and centres in the aerial wire. These lines of flux are alternately directed in a right-handed and left-handed direction, as seen from above. If we can imagine a being endowed with a kind of vision enabling him to see the lines of electric strain and magnetic flux in space, he, standing at any spot on the earth's surface, would see,

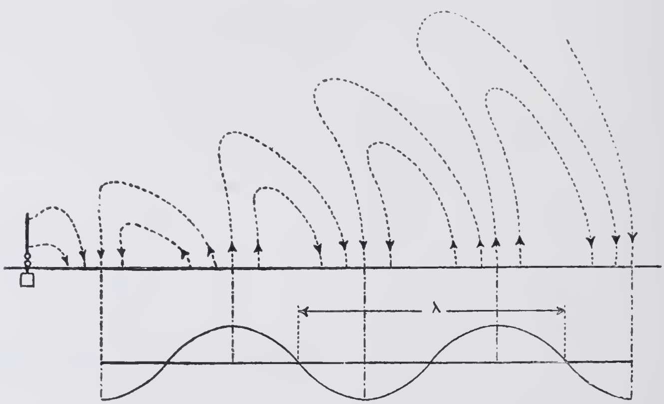


Fig. 23.—Diagram illustrating the Meaning of the Term Wave Length in Connection with the Electric Radiation from a Rod Oscillator.

when the radiator was in action, bunches or groups of lines of electric strain fly past. Near the earth's surface these strain lines would be vertical. Alternate groups of lines of strain would be oppositely directed, and the spectator would also see groups of lines of magnetic flux fly past, directed in a horizontal direction, or parallel to the earth's surface. These strain and flux lines would move with the velocity of light, and the distance between two successive maxima

of electric strain directed in the same direction would be the wave length of the wave. It will be seen, therefore, that the process is one which necessitates a perfectly free movement of electricity into and out of the earth at the base of the aerial, and experience shows that a "good earth," that is, a good low resistance and low inductance connection between the earth and the lower spark ball is important. Also, it has been found that a good conducting earth surface is required.

If we imagine a Hertz oscillator, consisting of a rod severed in the middle and having at that point a spark gap, to be bisected by a plane, so that the rods are perpendicular to the plane, then, since the electric force due to the oscillator is everywhere perpendicular to this median plane, we can make this plane conducting without affecting the distribution of the force on either side. The force systems on the two sides are then independent. We may consider this plane conducting sheet to be at zero potential, and we may imagine the force system on one side suppressed; still the distribution of electric force on the other side will not be affected.

We thus arrive at the conclusion that if a vertical rod is set up in the air, and at its lower end there is a spark ball in apposition to another spark ball connected to an earth plate, this arrangement constitutes electrically one-half of a Hertz oscillator. The antenna above the earth is said to be electrically "reflected" in the earth's surface, and the electromagnetic effect at any distant point is that due to the electrical oscillations in the antenna itself and to its "image" reflected in the earth's surface.

The assumption here made is that the earth is a good conductor, and this is valid for damp soil or sea surface. We shall return again, in Chap. VIII. (see § 14), to the consideration of the influence of the earth and of the atmosphere above it on electric wave propagation, in considering the actual apparatus used in wireless telegraphy by electric waves.

12. Theory of a Rod-shaped Oscillator.—The theory given by Hertz applied to an ideal oscillator in which two equal and opposite electric charges were supposed to reside in two small spheres separated by a short linear conductor with a spark gap in it. The electric moment was taken as the product of either charge and the length of the oscillator. This ideal case, however, does not quite correspond with the practical case as exhibited in wireless telegraphy. In this latter case we have as oscillator in its simplest form a vertical wire or rod having a spark gap at its lower end, and the lower spark ball connected to a good earth. This, as we have seen, may be regarded as half a complete linear oscillator consisting of two rods placed in line with each other, their inner ends provided with spark balls and placed in apposition. We require, therefore, the theory of a linear or rod oscillator. This has been given by several writers, particularly in complete form by M. Abraham[25] and by H. M. Macdonald.[26]

Abraham's memoir on the subject is long and abstruse, and almost

[25] M. Abraham, "Electrischen Schwingungen um einen stabförmigen Leiter behandelt nach der Maxwell'schen Theorie," *Annalen der Physik*, 1898, vol. 66, p. 435.

[26] H. M. Macdonald, "Electric Waves," Chap. X.

impossible to abstract adequately. His method of treatment, however, is as follows: To bring the problem within the grasp of analysis, he considers the rod to be an ellipsoid of revolution symmetrical round its major axis, the eccentricity of this ellipsoid being very large. The ratio of the semi-minor axis to the semi-major axis is therefore a very small fraction, the square of which may be neglected. As the external effects will be symmetrical with respect to the major axis, it suffices to consider the problem as one in two dimensions. The outline of the conductor is therefore taken as an ellipse, and the half distance between the foci is taken as the unit of length. A system of elliptical co-ordinates is then adopted in which confocal ellipses are described round the elliptical conductor, and confocal hyperbolas cut these ellipses orthogonally. The electric and magnetic forces in the space outside the aerial must therefore satisfy the equations of Maxwell, and the lines of electric force must terminate on the conductor normally to its surface. These equations are then written down in terms of the system of elliptical co-ordinates selected.

It is then shown that the free time period of oscillation of such a rod-shaped oscillator varies as the square root of the dielectric constant of the surrounding medium, but that the logarithmic decrement is independent of the nature of the medium.

It follows that the wave length of the waves sent out into the surrounding medium is independent of the dielectric constant of that medium, for the wave length is the product of the velocity and time period. Now, the wave velocity varies inversely as the square root of the dielectric constant, and since the period varies directly as the same quantity, the wave length is constant. Again, Abraham shows that the time periods of geometrically similar oscillators are proportional to their length, whilst their logarithmic decrements are the same.

He takes as the meridian section of his oscillator an ellipse having a semi-minor axis, b, and a semi-interfocal distance, 1, such that b^2 may be neglected in comparison with unity.

The quantity $\dfrac{1}{4\log_\epsilon\left(\dfrac{2}{b}\right)}$, or $\dfrac{1}{4\log_\epsilon\left(\dfrac{2l}{d}\right)}$, where l is the length of the wire and d its diameter, is then denoted by e, and it is then shown that for such an oscillator the fundamental wave length is approximately equal to twice the length of the rod, also that the damping by radiation diminishes as the thickness of the rod decreases, and, moreover, that the damping is less for the higher harmonics than for the fundamental.[27]

Abraham denotes the fundamental frequency n by unity, and the harmonics by $n = 2$, $n = 3$, etc.

He then shows that the logarithmic decrement *per complete period* (δ_n), where n is the order of the oscillation, viz. whether fundamental or higher, is given by the expressions—

[27] Abraham shows, as also does Macdonald, that the length of the wave is rather greater than twice the length of the rod. Macdonald shows it to be 2·5 times nearly. See H. M. Macdonald, "Electric Waves," p. 111.

$$\delta_1 = 9{\cdot}74\, e = \frac{2{\cdot}44}{4 \log_\epsilon \frac{2l}{r}}, \qquad \delta_2 = 6{\cdot}23\, e,$$

and generally, $$\delta_n = \frac{9{\cdot}66 + 4 \log_\epsilon (n+1)}{n+1} e \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

Thus, for instance, if we consider a vertical Marconi aerial wire of which the height is 180 feet and diameter 0·1 inch, we may consider the vertical section of this wire as the meridional section to be a semi-ellipse, of which the semi-interfocal distance is 2160 inches, which is the length of the wire. The semi-diameter is then 0·05 inch, and the value of b or the semi-minor axis of the ellipse is then $\frac{1}{10800}$, or nearly 0·0001. Hence we have—

$$e = \frac{1}{4 \log_\epsilon \left(\frac{2}{b}\right)} = \frac{1}{40} \text{ (nearly)}$$

$$\text{Hence} \quad \delta_1 = 0{\cdot}243, \quad \delta_2 = 0{\cdot}156$$

Accordingly, the fundamental decrement per *half period* would be 0·122, and this agrees with the results of the calculation given in Chap. III. § 8.

A very interesting paper has been published by F. Hack,[28] which supplements that of M. Abraham by delineating graphically the form of the lines of electric force round a linear or rod oscillator.

Hack takes the expressions derived by Abraham and applies them in the case of an infinitely thin rod for which the quantity denoted by $e = 0$, and deduces an equation for the lines of electric force due to the fundamental oscillation in the form—

$$\cos \frac{\pi y}{2} \cos \frac{\pi(ut - x)}{2} = C_1$$

where x and y are the elliptical co-ordinates of a point in the meridional plane, u is the velocity of radiation, and C_1 is a constant.

The diagrams in Figs. 1 to 4, Plate VI., represent the form of the lines of electric force round the linear oscillator for epochs $t = 0$, $t = \frac{1}{2u}$, $t = \frac{1}{u}$, $t = \frac{3}{2u}$. In this case the fundamental wave length $\lambda_1 = 4$, unity representing the half length of the rod.

As in the case of the diagrams given by Hertz, the above diagrams by Hack show that the wave-making process consists in the detachment of loops or closed lines of electric force, and that the true wave state is not established within a distance equal to about half a wave length.

If we suppose these diagrams traversed by a horizontal line, then all that part of the diagrams above that horizontal line will represent the distribution of electric force round a Marconi aerial wire or antenna at various stages during the oscillation.

[28] See F. Hack, "Das Elektromagnetische Feld in der Umgebung eines linearen Oszillators," *Annalen der Physik*, 1904, vol. 14, p. 539.

Hack has also (*loc. cit.*) given an additional very interesting series of diagrams showing the distribution of the electric force round the rod oscillator when the oscillations are harmonics (see Figs. 5 to 12, Plate VI.). Thus, for the first harmonic ($n = 2$) the equation to the lines of electric force is given by—

$$\sin \pi y \sin (ut - x) = C_2$$

and Hack gives a series of four diagrams showing the distribution of the electric force corresponding to the times—

$$t = 0, \quad t = \frac{1}{4u}, \quad t = \frac{1}{2u}, \quad t = \frac{3}{4u}$$

where u is the velocity of radiation.

These are shown in Figs. 5 to 8, Plate VI.

In this case the wave length $\lambda_2 = 2$, unity representing the half length of the rod.

Again, for the second harmonic ($n = 3$) he also gives the electric force distribution. This case is important, because the second harmonic for the finite rod is the first harmonic for the rod earthed at one end, so that the case when the frequency is three times that of the fundamental is a practical case which concerns us in wireless telegraphy. Hack shows that the Abraham equations reduce in this last case to the form—

$$\cos \frac{3\pi y}{2} \cos \frac{3\pi}{2}(ut - x) = C_3$$

The wave length λ_3 is $\frac{4}{3}$ of the half length of the rod.

This force system is represented by the four diagrams in Figs. 9 to 12, Plate VI., for the epochs $t = 0$, $t = \frac{1}{6u}$, $t = \frac{1}{3u}$, $t = \frac{1}{2u}$.

It will be seen that the wave production consists in sending out as usual closed loops of electric force.

If we take the force distribution in the upper half of each diagram, we have a representation of the system of lines of electric force sent out by a Marconi aerial when the oscillations are the first or first odd harmonic. The force system then consists partly of closed loops of electric force and partly of semi-loops of electric force with their ends on the earth surface. These semi-loops travel round the earth's surface or curvature, but the closed loops are shot off obliquely into space. It might be worth while to try whether the use of an inclined metal sheet or screen of wires so placed as to reflect this upward oblique radiation into a horizontal position would not result in greater energy being delivered to the receiving station.

By means of a cinematograph it is possible to throw on the screen a representation of the moving lines of electric force of a Hertzian oscillator or Marconi aerial in operation. In this case a series of diagrams have to be prepared similar to those in the Figs. 1 to 56, Plates II., III., IV., and V. (see end of this chapter), only delineated for much closer intervals of time. The whole periodic time must be divided into twenty or thirty parts, and diagrams

delineated, representing the exact state of the field of electric force for these instants. When such a series of diagrams is photographed on a celluloid strip and sent through a cinematograph lantern, we see on the screen a "living picture" of the Hertzian oscillator or Marconi aerial in electrical oscillation, and can witness the pulsation of the lines of electric force, and the radiation or throwing off of the loops or semi-loops of electric strain.

13. The Radiation from a Closed or Magnetic Oscillator.—As already explained, a closed oscillation circuit is one which consists of a condenser, the plates of which are very near together, and are also connected by a loop or circuit of wire. If oscillations are set up in this circuit then, although the plates of the condenser are charged alternately with charges of opposite sign, yet being near together their charges practically neutralize each other in external space as far as regards the production of electrostatic potential. The effect which is produced is nearly all due to the current in the nearly closed circuit. Hence there is a vector potential but no scalar potential distribution. Nevertheless, such a closed oscillator can create both electric and magnetic forces, and radiate electromagnetic waves into surrounding space. An extreme case of such a closed oscillatory circuit is a small, square, closed circuit formed by placing in contiguity four Hertzian oscillators with spheres or ends in contact, and assuming that the oscillations in each separate oscillator are simultaneous and directed in the same direction. This does not differ in effect from a simple closed conductive circuit assumed to be the seat of a high-frequency current. It is interesting to note that the mathematical problem of ascertaining the external effect of such a circuit was considered by the late Professor G. F. Fitzgerald prior to the date of Hertz's researches, and he showed that such a circuit could radiate electromagnetic energy.[29] We can easily obtain expressions for the electric and magnetic forces produced by such an oscillator by considering a small square circuit of side $\delta z = \delta y$ placed with its centre at the origin (see Fig. 24), each side consisting of a small Hertzian oscillator of electric moment ϕ. Let the oscillator be traversed by an alternating current of maximum value, I, and let n stand for 2π times the frequency as before. Let M denote the value of $I\delta y\delta z$ or the products of the maximum current, and the area of the oscillator, and let this product be called the *magnetic moment* of the oscillator. Then, since $\phi = Q\delta y = Q\delta z$, and since $I = Qn$, we have $\frac{M}{n} = \phi\delta y = Q\delta z$. Also, since the oscillator produces no scalar

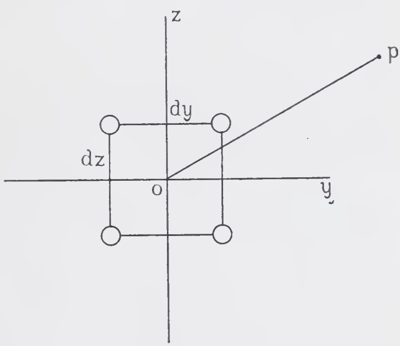


Fig. 24.

[29] See the scientific writings of the late Prof. G. F. Fitzgerald edited by Prof. J. Larmor, Sec. R.S., p. 128.

potential, and since the currents in it are wholly on the place of yz, we have $V = 0$, $F = 0$, but we have components of the vector potential G and H parallel to the currents in the two sides of the square, which can easily be shown to have values—

$$G = \phi \frac{d^2\Pi}{dzdt}\delta z, \qquad H = -\phi \frac{d^2\Pi}{dydt}\delta z$$

Where Π stands as before for $\frac{\sin(mr - nt)}{r}$.[30] Accordingly, when we substitute these values in the Maxwellian equations for the electric and magnetic forces given as in equations (20) and (21), we have—

$$\left.\begin{aligned} X &= 0 \\ Y &= -\frac{AM}{n}\frac{d^3\Pi}{dzdt^2} \\ Z &= \frac{AM}{n}\frac{d^3\Pi}{dydt^2} \end{aligned}\right\} \quad (72) \qquad \left.\begin{aligned} \alpha &= -\frac{M}{n}\left(\frac{d^3\Pi}{dy^2dt} + \frac{d^3\Pi}{dz^2dt}\right) \\ \beta &= \frac{M}{n}\frac{d^3\Pi}{dxdydt} \\ \gamma &= \frac{M}{n}\frac{d^3\Pi}{dxdzdt} \end{aligned}\right\} \quad (73)$$

The coefficient $A = \frac{1}{u}$ appears in the expressions for the electric force, because M being in electromagnetic units we must divide by 3×10^{10} to obtain the values of Y and Z in electrostatic units.

If these equations, (72) and (73), are compared with the corresponding equations (27) and (28) in § 7, it will be seen that the two sets differ as follows. For the closed oscillator we have the same expressions for the electric force components as for the magnetic components of the linear oscillator, with the exception that in the closed circuit everything is symmetrical with respect to the x axis, and in the case of the open oscillator with respect to the z axis. Again the expressions for the magnetic force components of the closed oscillator are identical with those for the electric force components of the open oscillator, with the exception that z takes the place of x.

Hence it is clear that the oscillations in the closed oscillator give rise to electromagnetic radiation, as in the case of the open oscillator, with the difference that the electric forces and magnetic forces change places. The open oscillator has rings or circles of magnetic force surrounding its symmetrical or z axis, and the closed oscillator has rings or circles of electric force surrounding its symmetrical or x axis, whilst the lines of magnetic force of the closed oscillator are similar in form to the electric lines of the open one.

There is, however, an immense difference between the two cases, viz. in the energy radiated outwards in each case per unit of time. It is clear, from the symmetry of the two cases, without any long detailed proof, that since the energy sent out by the open oscillator per complete period is expressed by $W = \frac{16\phi^2\pi^4}{3\lambda^3}$, where ϕ is the

[30] See J. A. Fleming, "A Note on the Theory of Directive Antennæ or Unsymmetrical Hertzian Oscillators." *Proc. Roy. Soc. Lond.*, vol. 78, A., 1906, p. 3.

electric moment of the open oscillator, the energy sent out per period by the closed oscillator must be equal to $\frac{16M^2\pi^4}{3\lambda^3}$, where M is the magnetic moment of the closed circuit. If detailed proof is required, the reader may be referred to a series of three articles by the author on "The Elementary Theory of Electric Oscillators," published in *The Electrician*, vol. lix., Sept. 27, Oct. 4, 11, 1907, pp. 936, 976, and 1016.

For the purposes of comparison we can put these formulæ in a more convenient form. Let us suppose the open oscillator to have a length l, and that the capacity of each end sphere, or half of the oscillator with respect to the other, be denoted by C, and the maximum potential difference of the spheres is V. If V is reckoned in volts, then $\frac{V}{300}$ is the P.D. in electrostatic units, and if C is in microfarads, then $9 \times 10^5 C$ is the capacity in electrostatic units. Hence the electric moment $\phi = 3000CVl$.

Let the current in the centre of the oscillator have a maximum value A, and let it be in the form of undamped sinoidal oscillations, so that $A = \frac{nCV}{10^6}$, where $n = 2\pi$ times the frequency N. Then, if a is the R.M.S. value of the current, $a = \frac{A}{\sqrt{2}}$, and the energy e radiated per period in ergs is given by—

$$e = 4\pi^2 10^8 \frac{l^2}{\lambda^2}\frac{A^2}{N} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (74)$$

and the radiation in watts w is given by—

$$w = 40\pi^2 \frac{l^2}{\lambda^2} A^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (75)$$

Remembering that $\pi^2 = 9{\cdot}87$, and $N\lambda = 3 \times 10^{10}$, we have—

$$e = 0{\cdot}2632 \frac{l^2}{\lambda^2} a^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (76)$$

$$w = 789{\cdot}6 \frac{l^2}{\lambda^2} a^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (77)$$

In the case of the closed circuit, if we assume it to be a square circuit, having a length of side l, and therefore an area l^2, and if the current in it is an alternating current amperes of frequency N, maximum value A, and root-mean-square value $a = \frac{A}{\sqrt{2}}$, we have for the magnetic moment M, $M = \frac{Al^2}{10}$, and hence for the energy in ergs sent out per period—

$$e = 10{\cdot}4 \frac{l^4 a^2}{\lambda^4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (78)$$

and the radiation in watts is—

$$w = 31200 \frac{l^4 a^2}{\lambda^4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (79)$$

We can then write the formulæ (77) and (79) for the radiation in the two cases open and closed, as follows :—

$$w = 87 \times 10^{-20} a^2 l^2 \mathrm{N}^2 \text{ (for the open or electric oscillator)} \quad . \quad (80)$$

$$w = 4 \times 10^{-38} a^2 l^4 \mathrm{N}^4 \text{ (for the closed or magnetic oscillator)} \quad . \quad (81)$$

These formulæ show us that for the same mean-square-current, linear dimensions, and frequency, the radiation of the open oscillator is immensely greater than that of the closed oscillator, provided that the frequency is not very high. Also they show us that the radiation of the closed oscillator increases very much faster with the frequency than that of the open oscillator.

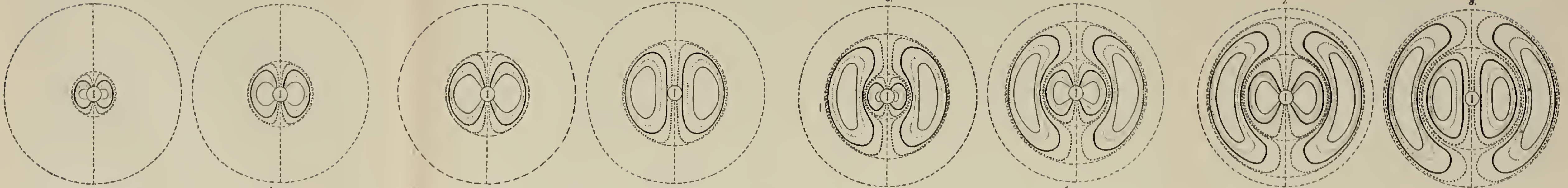
In the case of an open oscillator consisting of a simple straight coil with spark gap in the centre, there is a definite relation between the length l and the wave length emitted, which is such that $\frac{l}{\lambda}$ is approximately 0·4. Hence for such an oscillator we have $w = 126a^2$, or the radiation in watts depends only on the mean square value of the current at the centre.

The formula would, however, require some correction in the constant before applying it to a real linear antenna, because it has been obtained on the assumption that the oscillator is short, and the current at all points in it the same. This, however, is not the case, for the current is a maximum at the centre and zero at the ends.

We shall defer the consideration of the case of bent antennæ until a later chapter, when considering the problem of directive radiotelegraphy.

PLATE II.—DIAGRAMS SHOWING THE FORM OF THE LINES OF ELECTRIC FORCE ROUND A HERTZIAN DUMB-BELL OSCILLATOR FOR VARIOUS EPOCHS DURING SEVEN COMPLETE PERIODS, BY PROFESSOR KARL PEARSON, F.R.S., AND MISS ALICE LEE.

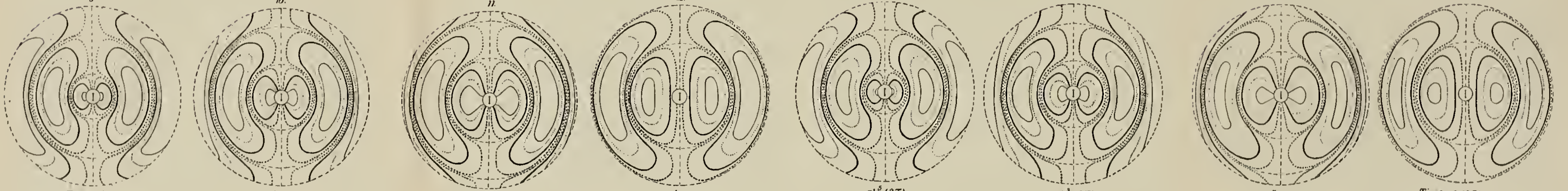
1. 2. 3 4 5. 6. 7. 8.



Time = $\frac{1}{8}$ Period = $\frac{1}{8}$ (2T) — $=\frac{1}{4}$ (2T) — $=\frac{3}{8}$ (2T) — $=\frac{1}{2}$ (2T) — $=\frac{5}{8}$ (2T) — $=\frac{6}{8}$ (2T) — $=\frac{7}{8}$ 2T) — Time = 1 (2T)

First Period.

9 10. 11. 12. 13 14. 15. 16.

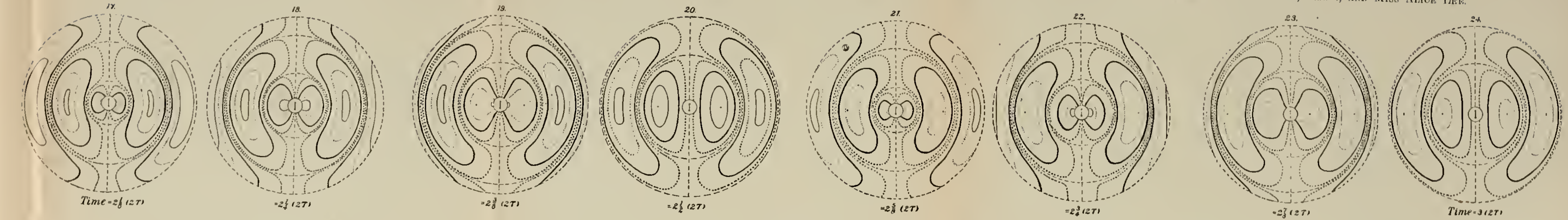


Time = $1\frac{1}{8}$ (2T) — $=1\frac{1}{4}$ (2T) — $=1\frac{3}{8}$ (2T) — $=1\frac{1}{2}$ (2T) — $=1\frac{5}{8}$ (2T) — $=1\frac{3}{4}$ (2T) — $=1\frac{7}{8}$ (2T) — Time = 2 (2T)

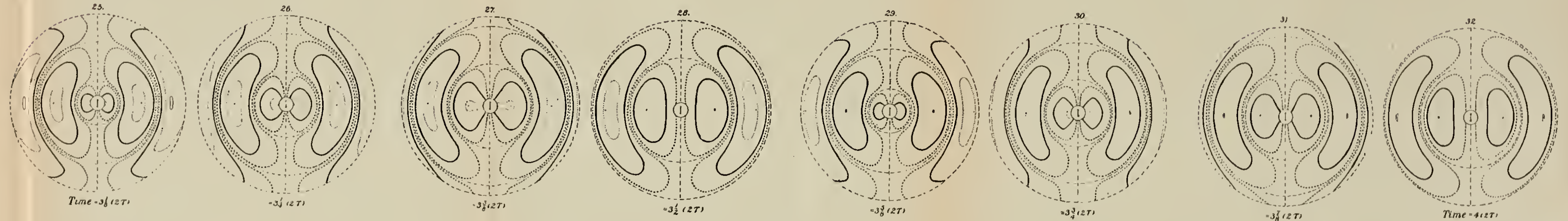
Second Period.

[To face p. 116.

PLATE III.—DIAGRAMS SHOWING THE FORM OF THE LINES OF ELECTRIC FORCE ROUND A HERTZIAN DUMB-BELL OSCILLATOR FOR VARIOUS EPOCHS DURING SEVEN COMPLETE PERIODS, BY PROFESSOR KARL PEARSON, F.R.S., AND MISS ALICE LEE.



Third Period.



Fourth Period.

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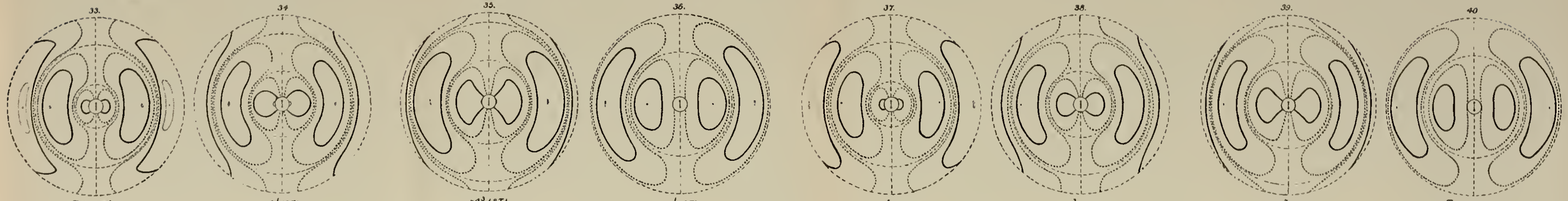
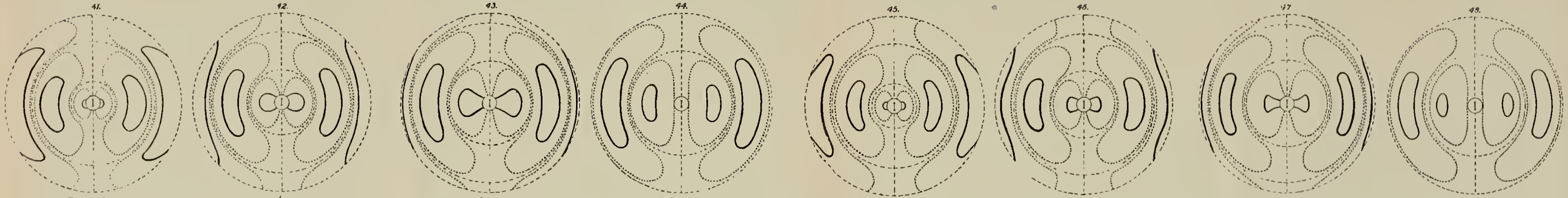
PLATE IV.—DIAGRAMS SHOWING THE FORM OF THE LINES OF ELECTRIC FORCE ROUND A HERTZIAN DUMB-BELL OSCILLATOR FOR VARIOUS EPOCHS DURING SEVEN COMPLETE PERIODS, BY PROFESSOR KARL PEARSON, F.R.S., AND MISS ALICE LEE.



Time $= 4\frac{1}{8}(2T)$ $= 4\frac{1}{4}(2T)$ $= 4\frac{3}{8}(2T)$ $= 4\frac{1}{2}(2T)$ $= 4\frac{5}{8}(2T)$ $= 4\frac{3}{4}(2T)$ $= 4\frac{7}{8}(2T)$ Time $= 5(2T)$

Fifth Period.

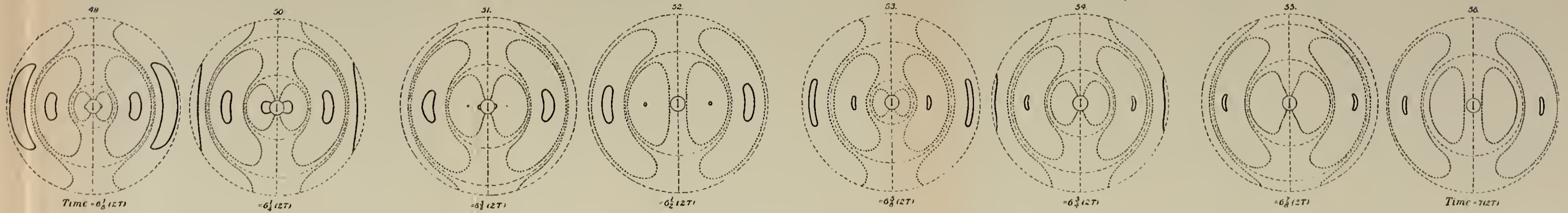


Time $= 5\frac{1}{8}(2T)$ $= 5\frac{1}{4}(2T)$ $= 5\frac{3}{8}(2T)$ $= 5\frac{1}{2}(2T)$ $= 5\frac{5}{8}(2T)$ $= 5\frac{3}{4}(2T)$ $= 5\frac{7}{8}(2T)$ Time $= 6(2T)$

Sixth Period.

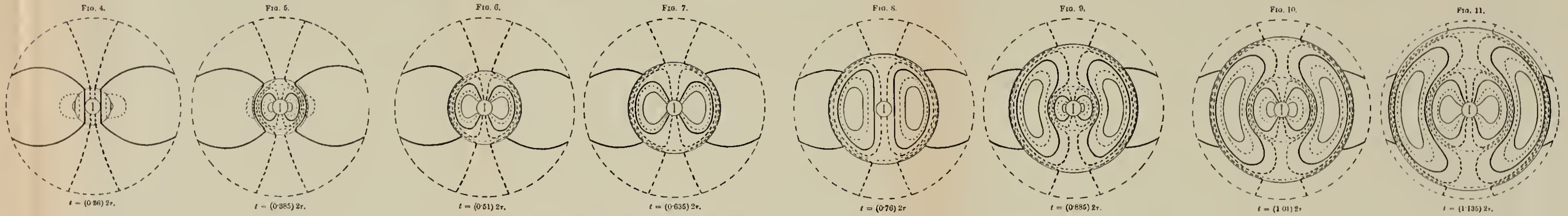
[*To face p.* 116.

PLATE V.—Diagrams showing the Form of the Lines of Electric Force round a Hertzian Dumb-bell Oscillator for Various Epochs during Seven Complete Periods, by Professor Karl Pearson, F.R.S., and Miss Alice Lee.



Seventh Period.

Diagrams showing the Advancing Wave Front round a Hertzian Dumb-bell Oscillator for Various Epochs, by Professor A. E. H. Love, F.R.S.



The fine continuous circle is the wave front, and the above diagrams 4 to 11, correspond with the diagrams 4 to 11 of Pearson and Lee in Plate II.

[*To face p.* 416.

PLATE VI. DIAGRAMS SHOWING THE FORM OF THE LINES OF ELECTRIC FORCE ROUND A ROD OSCILLATOR FOR VARIOUS EPOCHS DURING THE FUNDAMENTAL, FIRST, AND SECOND HARMONIC OSCILLATIONS.
DRAWN BY DR. F. HACK FROM THE EQUATIONS OBTAINED BY M. ABRAHAM.

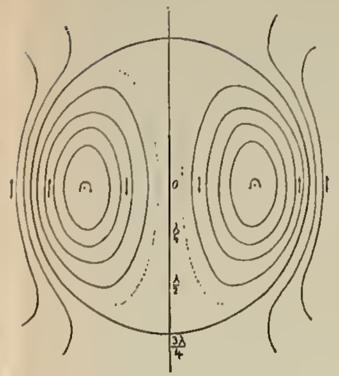


FIG. 1.—$t = 0$.

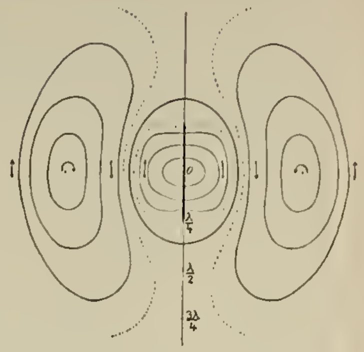


FIG. 2.—$t = \frac{1}{2u}$.

FIG. 5.—$t = 0$.

FIG. 6.—$t = \frac{1}{4u}$.

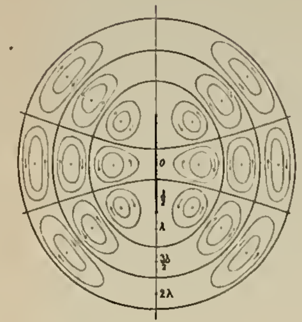


FIG. 9.—$t = 0$.

FIG. 10.—$t = \frac{1}{6u}$.

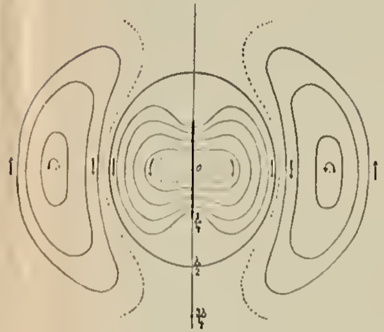


FIG. 3.—$t = \frac{1}{u}$.

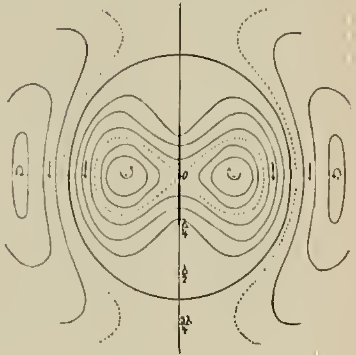


FIG. 4.—$t = \frac{3}{2u}$.

Fundamental Oscillation.

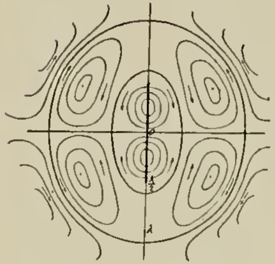


FIG. 7.—$t = \frac{1}{2u}$.

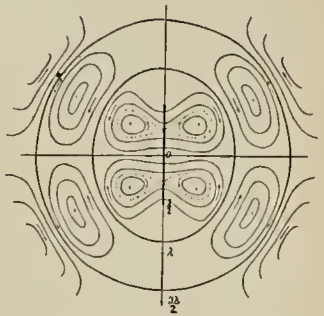


FIG. 8.—$t = \frac{3}{4u}$.

First Harmonic Oscillation.

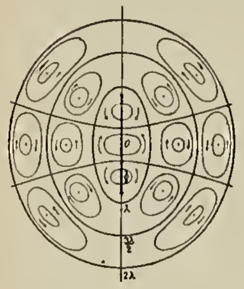


FIG. 11.—$t = \frac{1}{3u}$.

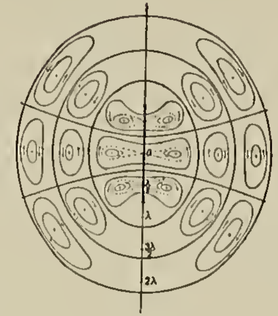


FIG. 12. $t = \frac{1}{2u}$.

Second Harmonic Oscillation.

The thick vertical black line across the centre of the diagram represents the Rod Oscillator.

[To face p. 416.

CHAPTER VI

DETECTION AND MEASUREMENT OF ELECTRIC WAVES

1. Appliances for detecting Electric Waves.—When the length of electric waves falls within a certain limited range, they are able to affect directly organs of sensation with which we are provided. Thus, if their wave length is anything between $0{\cdot}43\mu$ and $0{\cdot}75\mu$ (where μ denotes 1 micron or 0·001 of a millimetre) they affect the retina of the normal human eye and produce the sensation of light, the wave length determining the sensation of colour which we experience. This range of wave lengths barely covers one octave of radiation.

If the waves are sufficiently strong and have wave lengths rather greater than about $0{\cdot}5\mu$, they produce a sensation of heat when falling upon the skin. It is not yet known precisely how far down the gamut of electric waves this power extends, but it is certain that when the waves have a wave length of even a few millimetres they excite no sensation of heat when falling upon the human skin. Hence we may say that electric waves of the length with which we are chiefly concerned in this treatise do not directly affect any of our bodily organs. If, then, we are to detect their presence, it can only be in virtue of some change or action which they produce upon material substances or some device or apparatus arranged for this purpose.[1]

We have already seen that an electric wave consists of a periodic or cyclical electric displacement which calls forth a corresponding magnetic flux, these two component vectors being at right angles to each other, and periodic in space as well as time. We may, therefore, detect the wave presence either by the production of some physical effect due to its electric force or to its magnetic force. As the wave sweeps through space, there will be at any instant at any place through which it passes a momentary alternating electric force accompanied by a similar magnetic force at right angles to it, the plane in which these lie being at right angles to the direction of propagation of the wave. All wave-detecting devices are accordingly devices for detecting the momentary existence of electric or magnetic force in space. Any apparatus, therefore, which is very sensitive to rapidly reversed electric or magnetic forces may be adapted for use as a wave detector.

[1] Collectively these devices may be termed *cymoscopes*, from κῦμα, a wave.

Roughly speaking, we may classify the devices that have been proposed or used into the following groups :—

1. Spark detectors.
2. Contact detectors.
3. Thermal detectors.
4. Magnetic detectors.
5. Electrolytic detectors.
6. Electrodynamic detectors.
7. Rectifying detectors.

The above classification is not exhaustive, but it is sufficient for the present purposes of description. It should, however, be noted that in most cases the instrument or device we call a wave detector can only be used to detect the presence of electromagnetic waves in space when associated with a long collecting wire or wires called an *antenna* or *aerial*. It is in these wires that the wave generates, when passing across them, an alternating electromotive force or current, and the appliance we call the wave detector in reality is only a very sensitive alternating current voltmeter or ammeter, which, inserted across a condenser or in the wave-collecting wire, detects the existence of the wave by revealing the presence of this high-frequency electromotive force or current in the wire. In some cases the detector is actuated by a current which passes through it, and in others by the difference in potential between its ends. Hence a broad classification of wave detectors is into *current-operated* and *potential-operated* devices.

2. Spark Detectors.—If a pair of metal wires or strips of tinfoil attached to a glass plate are placed in line with each other, and their inner ends terminated in spark balls or sharp points placed close together, we have an appliance which with some adjustment will detect the presence of strong electric waves.

If the rods or strips are so placed that when the electric wave traverses them the electric force is parallel to the rods, then these metal conductors integrate or add up the electric force existing all along their direction at any one instant, and the ends in apposition are at a difference of potential which depends on the length of the rods and the strength of the waves. As the rods have capacity with respect to each other, and also inductance depending on their length, they have a certain natural time period of oscillation.

If this is adjusted by shortening or lengthening the rods so as to agree with that of the incident wave, then resonance will come into play to increase the potential difference between them when a wave train sweeps over the rods having the same time period. Such resonant rods may be made by making one or more tubes fitting telescopically into each other so as to be lengthened or shortened within limits, the ends in apposition being provided with small spark balls capable of having their distance from each other adjusted by a screw (see Fig. 1).

These rods of adjustable length may be carried on an insulating fixture. When held with the rods parallel to the electric force component of an electric wave, minute electric sparks will make their appearance at the spark balls if these are sufficiently near together.

The arrangement can, however, only detect the presence of relatively powerful electric waves. In order to make any visible spark in

air between balls, however near, but not in contact, there must be a certain maximum potential difference, which for air at normal pressure is not far from 300 volts.

This was shown particularly by experiments made in the Cavendish Laboratory, Cambridge, by Mr. Peace.[2] Sir J. J. Thomson observes that in this respect gases resemble electrolytes, in that a certain definite difference of potential between the electrodes has to be exceeded before any current or discharge will pass. No matter, therefore, how near the spark balls may be placed, the electric force in the inter space, and along the region occupied by the rods, must be such that there is a difference of potential between the rods equal to 300 volts, or to 1 electrostatic unit of potential difference, at least if a visible spark is to occur.

The spark detector can, therefore, never be a very sensitive instrument.

Hertz's ring resonator with micrometer spark gap belongs to the same category and suffers under the same limitations. In fact, considering its comparative insensibility, it is marvellous that Hertz was able to accomplish with it all that he did.

There are, however, some occasions when a somewhat insensitive wave detector is needed, and in these cases a spark detector is useful. Since the spark length corresponds to the maximum potential difference

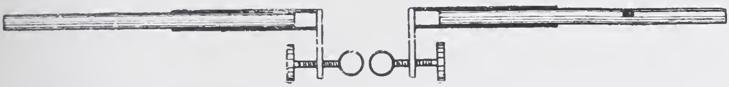


FIG. 1.—Sliding Rod Spark Cymoscope adjustable as to Time-period.

of the electrodes between which occurs, it follows that the maximum spark length which can be obtained, other things remaining the same, in a measure of the maximum value of the wave amplitude during the passage of the wave train.

The spark detector, though not very sensitive, has accordingly some valuable qualities. We can by it determine approximately the direction of the electric force in the wave—in other words, its plane of polarization—since it gives its maximum indication when the rods are placed parallel to the direction of that force. We can also roughly determine comparative maximum wave amplitudes, since, other things being equal, the wave with greatest maximum amplitude will create the longest spark.

3. Contact Detectors or Coherers.—The electric wave detecting device, commonly known as *a coherer*, has been the subject of much research. Many experimentalists in past years noticed that powdered metals or conducting substances in a state of fine division, or mixtures of metallic particles and other semi-conducting substances, were practically non-conductors under small electromotive forces when the mass was loosely compressed, but suddenly became possessed of good conductivity when a large electromotive force was applied to it.

[2] See "Recent Researches in Electricity and Magnetism," J. J. Thomson, p. 89.

Dr. K. E. Guthe traces this knowledge as far back as 1835, to Munk of Rosenschoeld, who clearly described the permanent increase in the electric conductivity of a mixture of tin filings, carbon, and other conductors resulting from the passage through it of the discharge of a Leyden jar.[3]

In 1852 the high resistance of a mass of loose metallic powder was observed by S. A. Varley, and it is said that four years later he had noticed a remarkable fall in the resistance of such material during a thunderstorm.[4]

In a British Patent Specification (No. 165 of 1866), C. and S. A. Varley described a device for protecting telegraphic instruments from lightning, which consisted of two copper points, nearly touching each other, set in a small box filled with powdered carbon. They say that the box may or may not be exhausted of its air. Also they observe that "powdered conducting matter offers great resistance to a current of moderate tension, but offers little resistance to a current of high tension."

This observation, however, did not attract the attention it deserved. In 1878 Professor D. E. Hughes was engaged on researches on the microphone, and in some of his experiments he employed a tube of glass, filled loosely with filings of zinc and silver, placed in series with a telephone and a single voltaic cell.[5] He appears to have discovered the important fact that such a tube, when so used, was sensitive to electric sparks at a distance as indicated by its sudden changes of conductivity. He subsequently stated that in these experiments he used a carbon-steel microphone which also proved to be very sensitive to an electric spark. He showed these experiments privately at the time to many scientific friends, but was discouraged from publishing the results, and it was not until twenty years afterwards that he publicly mentioned them.[6] Meanwhile, the same facts had come to the notice of other observers. In Italy, Professor T. Calzecchi-Onesti made experiments on the changes in electric conductivity of metallic powders, loosely aggregated, under the action of various electromotive forces. These he described in the Italian journal, *Il Nuovo Cimento*, 1884, vol. 16, p. 58, and 1885, vol. 17, p. 35, also in the *Journal de Physique*, 1886, vol. 5, p. 573.

He did not, however, carry knowledge much beyond the point at which it was left by the brothers Varley, viz. that whereas loosely compressed metallic filings constitute a poor electrical conductor under low electromotive forces, yet under the operation of the high electromotive forces such as that of an induction coil the conductivity is remarkably increased. These observations, moreover, attracted at the time no particular attention.

In 1890, Professor E. Branly, of Paris, published an account of

[3] See paper read before the St. Louis International Electrical Congress, 1904, by K. E. Guthe, on "Coherer Action"; see also *The Electrician*, 1904, vol. 54, p. 92.

[4] See *The Electrician* (Leader), vol. 40, p. 86.

[5] See D. E. Hughes, *Proc. Roy. Soc. Lond.*, May 9, 1878, vol. 27, p. 36.

[6] See a remarkable letter from Prof. Hughes in *The Electrician* of May 5, 1899, vol. 43, p. 40. An epitome of these important experiments made in 1879–1886 by Hughes is given in Fahie's "History of Wireless Telegraphy," p. 296. For a further reference to Hughes' work, see Chap. VII. § 1, of this treatise.

a very extensive series of observations on the same subject. Whilst confirming the work of previous observers, he added much new knowledge.[7] He made the extremely important and novel observation that an electric spark *at a distance* had the power of suddenly changing the electric conductivity of loose masses of powdered conductors. In some cases he observed that this change was an increase in conductivity, and in other cases a decrease. The majority of common metals exhibit the increase in conductivity, but the contact between lead and peroxide of lead becomes less conductive. To Professor Branly belongs the honour of giving to science a new weapon in the shape of a tube or box containing metallic filings rather loosely packed between metal plugs (see Fig. 2).

He showed that such a tube may be a conductor of very high resistance when the metallic filings are loosely arranged, but that if a discharge from a Leyden jar or other electric spark was made in its vicinity, the conductivity of the metallic powder was suddenly increased. He detected this change by connecting a galvanometer and single cell in series with the tube, and adjusting the pressure on the powder until no current would pass through it. Under the influence of a spark at a distance, the galvanometer needle then made a sudden deflection, showing the acquirement of conductivity by the mass of metallic filings.

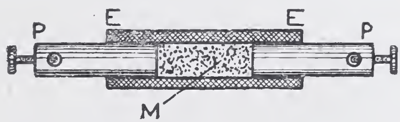


Fig. 2.—Branly Metallic Filings Tube or Cymoscope. E, tube of insulating material; P, P, metal plugs; M, metallic filings loosely packed.

Branly also found that the same effect occurred in the case of two slightly oxidized steel or copper wires laid across each other with light pressure. This loose or "imperfect contact" was found by him to be extraordinarily sensitive to a distant electric spark, dropping in resistance from some thousands of ohms to a few ohms, when an electric spark was made many yards away.

Branly's work did not, however, secure the notice it demanded until 1892, when Dr. Dawson Turner described Branly's experiments at a meeting of the British Association in Edinburgh, and his own additions to them.[8]

Dr. Dawson Turner's paper raised a discussion on the subject, and drew from Professor George Forbes an important question. He asked whether it was not possible that Hertz waves might in a similar manner break down the resistance of a tube of loose metallic filings. This question showed that the real cause of the phenomena noted by Branly had not yet been fully comprehended, and even then its importance was not appreciated. In the following year Mr. W. B. Croft exhibited Branly's experiments at a meeting of the Physical Society in London, and read a short paper on the action

[7] See E. Branly, *Comptes Rendus*, 1890, vol. 111, p. 785; also 1891, vol. 112, p. 90; or *La Lumière Électrique*, 1891, vol. 40, pp. 301, 506; or *The Electrician*, 1891, vol. 27, pp. 221, 448.

[8] See Dr. Dawson Turner, *The Electrician*, 1892, vol. 29, p. 432, "Experiments on the Electrical Resistance of Powdered Metals."

of electric radiation on copper filings.[9] He exhibited a glass tube containing copper filings joined in series with a galvanometer and a battery. When the filings were loosely arranged no current passed, but immediately an electric spark was made by an electrical machine at a little distance, the galvanometer was deflected, and remained deflected until the tube was tapped. He stated that he had tried different kinds of metallic filings. Aluminium and copper he found equally good, but iron not so good, and with carbon he obtained no effect at all. These facts themselves had already been observed by Branly, but the advance appeared to be a more definite recognition of the cause of the phenomena to be electric radiation falling on the tube. In this discussion Professor Minchin distinctly said the change was due to electric radiation, and not to the light of the spark. He stated that he had found his impulsion cells to be rendered sensitive to light by an electric spark 140 feet away. Mr. Croft called attention to the fact that the filings tube passed into a conductive state *before* the actual spark passed when the static electrical machine was set in motion.

This paper was followed shortly after by another by Professor G. M. Minchin, entitled "The Action of Electromagnetic Radiation on Films containing Metallic Powders."[10] He exhibited films of gelatine and collodion, impregnated with metallic powders. These were inserted in the circuit of a battery and galvanometer. He found that contact with an electrified body rendered the film conductive. In this paper Professor Minchin made definite reference to the Branly tube, and says that "the waves sent out from the spark at once render the column (of metallic filings) a conductor."

It is clear, therefore, that at the end of 1893 a few physicists, pre-eminently Professor Minchin, had clearly recognized that the action discovered by Branly had its origin in electric waves sent out from the spark.

This paper of Professor Minchin was followed by another from Sir Oliver Lodge, entitled, "On the sudden Acquisition of Conducting Power by a Series of Discrete Particles."[11] In this paper he alludes to an observation he had frequently made in connection with his experiment of the Syntonic Leyden jars, viz. that if the two metal knobs of the receiver were very close together, a battery and electric bell being in circuit, the occurrence of an electric oscillation in the circuit caused the knobs to come into good contact and made the electric bell ring. Four years previously, in 1889, Lodge had noticed that the passage of a spark between two metal plates in microphonic or imperfect contact caused them to weld together and

[9] See W. B. Croft, *Proc. Phys. Soc. Lond.*, vol. xii. p. 421.

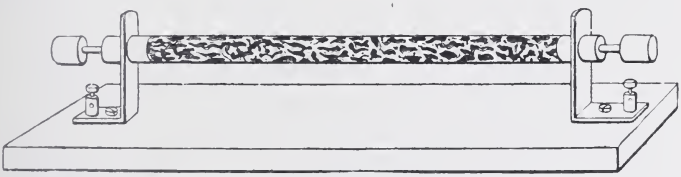
[10] See Prof. Minchin, *Proc. Phys. Soc. Lond.*, November 24, 1893, vol. xii. p. 455. Also *Phil. Mag.*, January, 1894, vol. 37, p. 90. A paper by Prof. Minchin will also be found in *The Electrician*, November 27, 1891, vol. 28, p. 85, on the "Detection of Electromagnetic Disturbances at Great Distances," in which he describes a form of cell, consisting of pieces of tinfoil specially prepared, placed in methyl alcohol, which generates an E.M.F. when exposed to light. It can be rendered insensitive by small shocks. When in this insensitive condition, Prof. Minchin found that the cell again became sensitive to light by the action of an electric spark at a distance.

[11] See *Proc. Phys. Soc. Lond.*, 1893, vol. xii. p. 461. See also *Phil. Mag.*, January, 1894, vol. 37, p. 24.

make good contact. There is, however, no clear proof that at this date (1889) Lodge had recognized that this action could be produced by electric radiation alone.

In June, 1894, Lodge gave a lecture at the Royal Institution, entitled "The Work of Hertz." In this lecture he described the Branly tube, and showed an instrument in which a light microphonic or imperfect electrical contact was made a good conducting one by the impact on it of electric waves. He also employed a tube loosely full of iron borings closed at the ends with metallic plugs, and this in the same manner exhibited improved conductivity when electric radiation fell upon it. Lodge then gave the name *coherer* to any device in which a loose or imperfectly conducting contact between pieces of metal was improved in conductivity by the impact on it of electric radiation. This lecture was the means of drawing attention strongly to the discoveries of Branly, and to the fact that a new and highly sensitive means of detecting electric radiation had been evolved.[12]

In the next year or two no very notable improvement took place in the construction of the coherer. In the form in which it was used by Lodge in 1894, the coherer consisted of a glass tube about 1 cm.



From "The Electrician."

FIG. 3.—Lodge Coherer or Electric Wave Detector.

or less in diameter, and 6 or 8 cms. in length, filled loosely with coarse filings or borings of iron or other metal contained between two metal plugs (see Fig. 3). Brass borings were tried, and various other metals, and the tube filled with air, hydrogen, or even exhausted. Lodge experimented with various forms of light contact between plates and points, such as a steel sewing-needle lightly resting on an aluminium plate, and with slightly oxidized steel rods lightly resting on each other.

The appliance in the above described forms was generally found to be a somewhat capricious instrument to use; in some conditions highly sensitive to distant electric sparks, and then without apparent reason becoming far less sensitive. It had in general been found that the metals most suitable were those which were slightly but not very oxidizable. Iron, steel, nickel, copper, or zinc filings or borings worked fairly well, but coherers made with gold, silver, platinum, or noble metals proved more difficult to handle.

Meanwhile, in 1894 and 1895, G. Marconi began his work in

[12] See *Proceedings of the Royal Institution*, 1894, vol. xiv. p. 321; also *The Electrician*, 1894, vol. 33, pp. 153, 186, 204. Lodge republished his 1894 Royal Institution lecture as a book, the first edition bearing the title, "The Work of Hertz and Some of his Successors." A second edition appeared in 1897, under the modified title, "Signalling across Space without Wires.

Italy, and turned his attention to the improvement of Branly's coherer. He carefully investigated the relative advantages of the various metals in regard to their suitability for making a metallic filings coherer, and he modified the form and size of the tube. Whereas others had used rather large tubes, filled with somewhat coarse filings or borings, he adopted a much smaller size of glass tube [13] (see Fig. 4), about 3 or 4 cms. long and about 5 mm. internal diameter. He placed in this two silver plugs fitting the tube tightly, and attached to these platinum wires which were sealed through the glass. The ends of these plugs were polished and slightly amalgamated with mercury. The ends of the plugs were brought within a couple of millimetres of each other. The interspace was about half filled with a small quantity of nickel and silver filings, 95 per cent. nickel, and 5 per cent. silver, carefully sifted so as to be of a certain degree of fineness. The glass tube was then exhausted and sealed. Subsequently he bevelled the edges of the silver plugs so as to make the interspace wedge-shaped. So improved and carefully

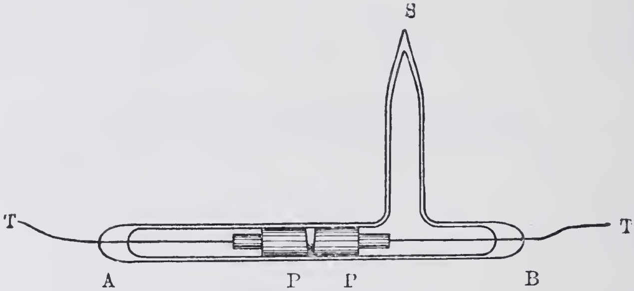


Fig. 4.—Marconi Sensitive Tube or Cymoscope. (*Full size.*) A, B, glass tube exhausted; T, T, platinum terminal wires; P, P, silver bevelled plugs; S, side tube for exhaustion.

made, the Marconi coherer proved to be a most sensitive electric wave-detecting device or cymoscope, far more certain in its action than anything which had previously been designed.

Marconi then proceeded to invent the devices for employing his sensitive tube as a relay upon a relay in a telegraphic instrument, and to use it for conducting wireless telegraphy in the manner described in the next chapter. The news of his success in this important practical application caused widespread interest in the subject of coherers.

Branly reasserted his claim to be the inventor of the metallic filings coherer, but he seems to have underrated the importance of Marconi's improvements.[14] Lodge, about this time, wrote a paper on the "History of the Coherer Principle," [15] in which he did something less than justice to the novelty and importance of Marconi's work.

[13] See British Patent Specification of G. Marconi, No. 12,039, of June 2, 1896.

[14] See E. Branly, "On the Electrical Conductivity of Discontinuous Conducting Substances," *Comptes Rendus*, December 6, 1897, vol. 125, p. 939; also *The Electrician*, 1897, vol 40, p. 333.

[15] See *The Electrician*, 1897, vol. 40, p. 87.

In January, 1896, Professor A. S. Popoff, of Cronstadt, Russia, communicated a paper to the *Journal of the Russian Physical and Chemical Society*, in which he described certain experiments made with a metallic filings coherer.[16] He made his sensitive tube of glass with two platinum leaves down opposite sides, the interspace being loosely filled with iron filings (see Fig. 5).

Popoff combined with this tube an arrangement for automatically tapping back the filings to a sensitive condition. As already stated, Branly observed that after the loose aggregations of imperfectly conducting metallic filings had been exposed to an electric spark and rendered thereby conductive, a slight tap or mechanical shock brought them back again into the high resistance or non-conductive condition.[17] Lodge had also noticed that when two brass knobs in microphonic contact had been caused to cohere by the passage of a small spark between them, the contact was destroyed by a slight mechanical shock.

Lodge had found that if a battery and electric bell were connected between the knobs and placed on the same stand, the mere mechanical vibration of the bell when the circuit was completed was sufficient to destroy the light contact of the knobs. When he subsequently came to employ the metallic filings coherer of Branly as an electric

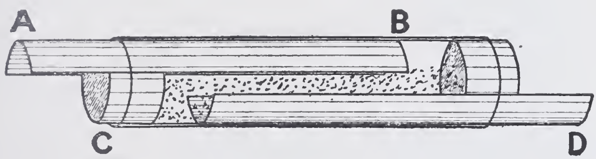


Fig. 5.—Popoff's Coherer.

wave detector, he arranged a "clockwork tapper consisting of a rotating spoke wheel driven by the clockwork of a Morse instrument, and giving to the filings tube or to a coherer a series of jerks at regular intervals"[18] (see Fig. 6). He states, however (*loc. cit.*) that "an electric bell mounted on the base of the filings tube was not found very satisfactory, because of the disturbances caused by the little sparks at its contact breaker to which the previous coarser knob arrangement had failed to respond."

Popoff, however, arranged an electric bell so that the hammer was made to tap the coherer tube lightly and administer to it the small shock required to make the filings decohere.

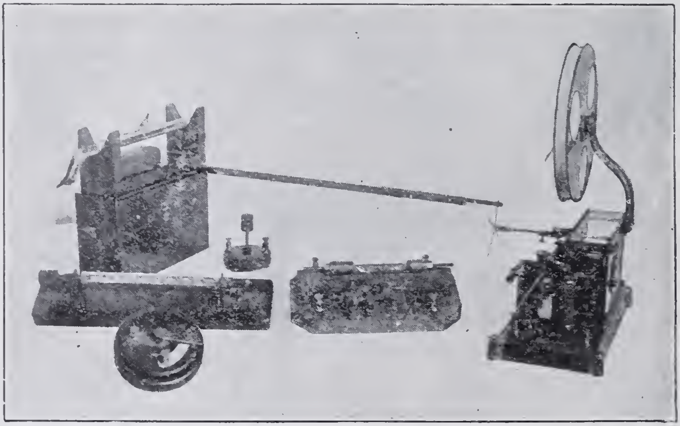
Popoff employed his filings tube to close the circuit of a telegraphic relay, and this, in turn, when actuated, set the electric bell

[16] *Journal of the Russian Physical and Chemical Society*, January, 1896, vol. 28.

[17] See a paper by E. Branly in *La Lumière Électrique*, May 16, 1891, translated in *The Electrician*, 1891, vol. 27, pp. 221, 448. The restoration of nonconductivity by a tap or shock is particularly mentioned. Also it is mentioned in the paper read by Dr. Dawson Turner to the British Association at Edinburgh, in August, 1892; see *The Electrician*, 1892, vol. 29, p. 432.

[18] See O. J. Lodge, "On the History of the Coherer Principle," *The Electrician*, 1897, vol. 40, p. 90. See also *The Electrician*, vol. 39, p. 687, for a photograph of this mechanical tapper, as exhibited at a meeting of the British Association at Oxford in 1897.

in operation so that its hammer struck the coherer tube [19] (see Fig. 7). The purpose which Popoff had in view was to study the phenomena of atmospheric electricity, and he employed the Branly filings tube as a means of detecting and making records of atmospheric electrical discharges at a distance. He states that the above-described apparatus was set up in July, 1895, at the Meteorological Observatory of the Forest Institution in St. Petersburgh. One end of the coherer was connected to a lightning conductor and the other end to the earth, and he further remarks that from July, 1895, to December, 1897, his apparatus worked well as a lightning recorder. He made the arrangement record by connecting in parallel with the electric bell an instrument in which a pen was caused to make marks on a moving band of paper when the circuit of an electromagnet was closed. We shall return to the consideration of Popoff's experiments in dealing with the question of electric wave telegraphy.



From "The Electrician."

FIG. 6.—Lodge's Arrangement for tapping back his Coherer Tube to Wave Sensitiveness by means of a Clockwork-driven Tapper.

Marconi had meanwhile filed an application for a British patent,[20] in which the details of his electric wave detector were particularly described. He also associated with its sensitive metallic filings tube a telegraphic relay and a single cell, so that when the tube passed into its conductive condition the circuit of the relay was closed. He points out that the metallic filings tube must not be traversed at any time by a current greater than about 1 milliampere. Hence his relay was wound with a wire of high resistance, and one having a resistance of 1000 ohms is usually employed. The relay, in turn, is made to close the circuit of an electromagnet which operates a tapping arrangement to bring back the tube continually to a sensitive condition. The details and adjustments of his tapper were designed with

[19] See a letter from Prof. A. Popoff, *The Electrician*, December 10, 1897, vol. 40, p. 235.

[20] No. 12,039, of June 2, 1896, "Application of Guglielmo Marconi for Improvements in Transmitting Electrical Impulses and Signals and in Apparatus therefor."

peculiar care. The tapper consists of an electromagnet having a vibrating armature like an electric bell, the armature carrying a

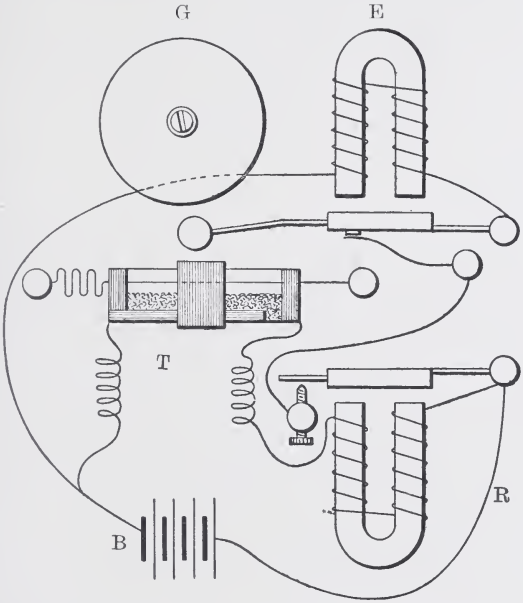


FIG. 7.—Popoff's Electromagnetic Tapper for tapping back the Metallic Filings Tube to Wave Sensitiveness. T, coherer; R, relay; E, electromagnetic tapper; B, battery; G, gong.

hammer consisting of a round brass knob on a stem. The electromagnet is so fixed on an incline plane that the blow administered to the sensitive tube is from below upwards (see Fig. 8). He added delicate screw adjustments by means of which the exact strength of the blow, and the rate at which they were given, could be precisely controlled. In addition to this, he overcame the difficulty mentioned by Lodge, by inserting in the circuit of the sensitive tube two choking coils of wire, the effect of which was to prevent the oscillations started by the minute sparks at the relay or vibrating hammer contacts, travelling back along the wires and causing coherence in the filings. The vibrating tapper and any other telegraphic printing or recording

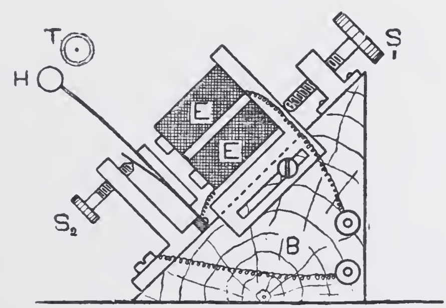


FIG. 8.—Marconi's Electromagnetic Tapper for tapping back his Sensitive Tube to a Receptive Condition. E, E, electromagnet; H, hammer; T, sensitive tube shown in section; S_1, S_2, adjusting screws.

instruments were worked in parallel by the relay by a set of dry cells, one separate cell being used in the circuit of the coherer and relay.

The cell in series with the relay and sensitive tube passed a current not exceeding a milliampere through the tube when the filings cohered under the action of an electric wave, and the circuit of the relay thereby closed caused the current from about eight other dry cells to work the tapper and Morse printer or recorder.

Marconi mounted the whole of this apparatus on one base board and enclosed it in a metal box to preserve it from the action of stray waves or sparks.

In this manner, towards the end of 1896 Marconi produced a compact self-contained cymoscope of greater sensitiveness and certainty of action than any which had previously been designed.

The results which he obtained with it when associated with his other inventions stimulated research in a remarkable manner. He came over from Italy to England and made known his improvements to Sir W. H. Preece, then the engineer-in-chief of the British Government Telegraph Department of the General Post Office. Sir W. H. Preece exhibited it at a lecture he gave at the Royal Institution on June 4, 1897, and stated that "Marconi has produced from known means a new electric eye, more delicate than any known electrical instrument, and a new system of telegraphy that will reach places hitherto inaccessible.[21]

4. Methods of detecting and recording the Passage of Electric Waves by Contact Detectors.—It has already been mentioned that Branly discovered the fact that whilst some kinds of loose or imperfect electrical contact are lowered in resistance by the creation of an electric spark near them, other descriptions of contact are caused to increase in resistance. This change is the result of an electric wave created by the spark. The alteration, whether to greater or less conductivity, is essentially due to the creation of an electric force at the imperfect contact. The change has, however, to be detected in some manner by, so to speak, testing the contact or contacts before and after the passage of the wave. We do this by applying to the imperfect contact a small external electromotive force in conjunction with some means for detecting an electric current. This external electromotive force must not exceed a certain small value, generally a fraction of a volt, or at most 1·5 to 2 volts, or else it will itself produce the change in conductivity without any assistance from a passing electric wave.

There are three methods by which we may explore and reveal the change in conductivity (if any) which has been produced in the sensitive conductor consisting of a loose or microphonic contact or contacts of some kind.

We may simply connect the coherer in series with a single cell, or with a shunted cell, and a detector, such as a galvanometer, or other direct telegraphic recorder, such as a syphon recorder, as used in submarine telegraphy. In the next place, we may, as already described, connect the sensitive device in series with a single cell and a delicate telegraphic relay. Such a relay should be one which

[21] See *Proc. Royal Institution*, 1897, vol. xv. p. 461, or *The Electrician*, vol. 39, p. 217.

operates with a current of not more than 1 milliampere, and, better still, with one-tenth of a milliampere. This relay can then be made to close the circuit of any form of ordinary printing or recording telegraphic instrument, such as a Morse inker or printer, which works with a single current. This plan is generally called the telegraphic receiver method.

In the third place, we may employ an ordinary magnetic or bell telephone in series with the sensitive device, coherer, or contact detector, a single voltaic cell and a high resistance, or else a shunted cell, being placed in the circuit. Then, when the sensitive device suddenly changes in conductivity, it either increases or diminishes suddenly the current through the circuit, and a *click* is heard in the telephone by a listener. Generally speaking, this last method, called the telephonic method of receiving, enables us to estimate smaller changes in the conductivity of the sensitive contact than the method with the relay. All these methods have, however, their own peculiar advantages. The direct or galvanometric method appeals to the eye, and is suitable for lecture or demonstration purposes. The telephonic method appeals to the ear, and is the most delicate. The method with the relay enables a permanent record of the signals or changes to be obtained on a Morse tape or in printed signs, and has much to recommend it. On the other hand, the numerous adjustments require more skill than when the telephonic method is used, and when the receipt of telegraphic messages is in question, many operators and inventors have given preference to the telephonic method. The circuit which contains the detector, battery, and relay, or other telegraphic instrument, may be called the *detector circuit.* It consists of three appliances connected in series.

(i.) Some source of electromotive force, viz. a voltaic cell or cells, thermopile or dynamo.

(ii.) Some device for indicating the presence or change in strength of an electric current, as, for instance, a galvanometer, telephone, or telegraphic relay or recorder.

(iii.) Some appliance for creating a variation in the strength of the above current, which is set in operation by electric oscillations, so that it either increases or decreases the resistance of the detector circuit, or increases or decreases the electromotive force in that circuit. This last device is called the *oscillation detector*, and it is connected also either directly or inductively with an *antenna* or wire in which the incident electric waves set up electric oscillations.

5. Various Forms of Coherer and Materials for their Construction.—The simplest form of contact detector is the crossed needle or single contact, originally described by Branly.[22] Lodge also found that a steel sewing-needle having its point lightly pressed against an aluminium plate made a fairly regular coherer.[23] When an electric wave passes over it, the point is welded to the plate, and the loose or imperfect contact becomes a good one, and will pass a current from a single cell through a galvanometer. It may here be

[22] See E. Branly, "Variations of Electric Conductivity under Electrical Influence," *The Electrician*, vol. 27, p. 222.

[23] See O. J. Lodge, "The History of the Coherer Principle," *The Electrician*, vol. 40, p. 90.

noted that the passage of the current is not necessary to create the coherence, it merely reveals it.

Branly found in 1891 that if a pair of slightly oxidized copper wires rest across one another, the contact resistance, when no pressure is applied, is very high (8000 ohms or so). It falls, however, to a few ohms (6 or 7) on the impact of an electric wave.

The objection, however, to a single contact from the point of view of telegraphy is the small detecting current which can be passed through the junction without damaging the sensitiveness of the contacts by welding them together too much. In this case it requires a considerable shock to effect severance, and the junction becomes less sensitive to electric waves. Subsequently, however, Branly found that a series of metal balls in light contact formed a good coherer.[24] He tried using small balls of soft iron placed in a glass tube. Thus ten balls showed an initial resistance of 990 ohms, which dropped to 60 ohms on passing a 1·5-mm. spark at a distance of 10 metres. He found hard steel balls still better, varying in contact resistance from 2000 to 100 ohms on passing a spark. A coherer of six hard steel balls, such as are used for bicycle bearings, is about as sensitive as a gold filings coherer, but to work well the decohering shock must be carefully regulated.

More recently he has devised a tripod coherer, consisting of a small metallic stool with three slightly oxidized legs.[25] This tripod stands on a polished steel plate, and arrangements are made to decohere it by tilting the little stool by an electro-magnet when the legs become cohered to the plate under the action of a wave. The ends of the legs must not be too heavily oxidized, and the stool must be very light in weight, so as to make bad contact with the plate until the impact of the wave improves it (see Fig. 9).

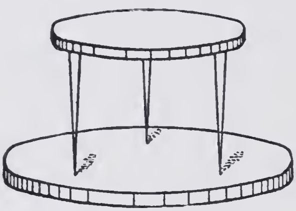


Fig. 9.—Branly's Tripod Coherer.

In the case of the ball coherer, variation of sensibility may be made by tilting the glass tube containing the balls to various inclinations, so as to make the balls press more or less heavily on each other.

In the case of metallic filings coherers, a variation in sensibility may be obtained by bevelling off the electrodes obliquely so as to make the gap wedge-shaped, as in the Marconi coherer.[26] The present form of Marconi telegraphic coherer is attached to a bone holder, consisting of a round bone rod with squared end, to which the coherer is lashed by silk threads. By taking hold of the glass "tail" of the coherer or sealed-off glass end by which the coherer is exhausted, it can be turned on its axis into various positions, so that the filings

[24] See E. Branly, "Ball Coherers," *Comptes Rendus*, 1899, vol. 128, p. 1089, or *Science Abstracts*, vol. ii. No. 1164.

[25] See Prof. E. Branly, "A Sensitive Coherer," *Comptes Rendus*, 1902, vol. 134, p. 1197, or *Science Abstracts*, 1902, vol. 5, p. 852.

[26] This device was very early employed by Marconi, but it has been patented again and again by various inventors. See German patent, No. 116,113, Class 21a, 1900. It has also been claimed by M. Tissot.

lie in a broader or narrower portion of the bevelled gap between the silver plugs. The sensibility is thereby altered within certain limits (see Fig. 10). Other ways of adjusting the sensibility of filings coherers have been devised. Thus M. Blondel constructed a coherer with a side tube or pocket (see Fig. 11) in which was placed a reserve of filings, and by shaking more or less of these into the gap

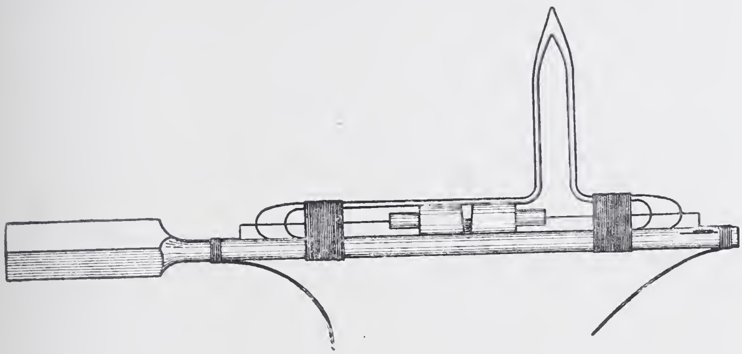
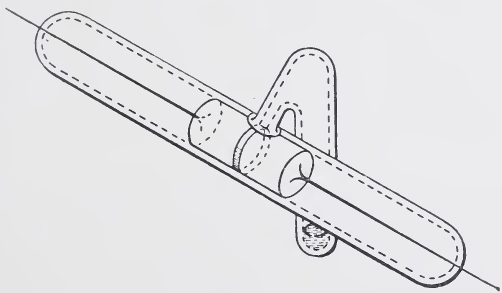


FIG. 10.—Marconi Sensitive Metallic Filings Tube or Cymoscope supported on a Bone Holder. (*Full size.*)

between the electrodes the desired variation could be produced.[27] A somewhat similar arrangement was tried by Lodge.

As regards materials for the construction of coherers, it seems to be generally agreed that the non-oxidizable or noble metals, such as gold, platinum, and silver, taken alone, are not well suited for



From the "Electrical Review."

FIG. 11.—Blondel Side-pocket Metallic Filings Coherer.

making telegraphic cymoscopes. All metals in the state of filings or fine borings exhibit the phenomena of coherence, but the non-oxidizable metals are too sensitive. On the other hand, the very oxidizable metals are too insensitive, and in some cases, such as potassium and arsenic, Professor J. C. Bose found a reversal of effect, viz. that under the action of electric waves the constant resistance between particles of these metals was increased, and not diminished, by the impact of an electric wave.

[27] See a letter from M. A. Blondel, *The Electrician*, 1899, vol. 43, p. 277.

It is a curious fact that the magnetic metals, nickel, iron, cobalt, in the order named, give better results than non-magnetic metals, whether used as filings in a tube or as ball or rod coherers. The best results are obtained when employing in a metallic filings tube a mixture of filings of a magnetic and a noble or unoxidizable metal; for example, a mixture of iron, nickel, or cobalt filings with a small percentage of silver, gold, or platinum filings, the mixture of nickel and silver giving, as Marconi has shown, a particularly good result.

The use of carbon for the construction of coherers has been much discussed. A British Patent Specification of Messrs. A. C. Brown and G. R. Neilson, No. 28,958, of December 17, 1896, one of the earliest taken out for improvements in electric wave telegraphy, mentions the employment of carbon granules or powder in a coherer in combination with a telephone as a means of detecting change in conductivity.

Some persons at one time declared that carbon could not be used in a Branly tube as a Hertzian wave receiver, and Branly himself makes no mention of it. Sir Oliver Lodge, in his book on "The Work of Hertz," mentions in a footnote that Professor Fitzgerald had succeeded in employing carbon, but no details of the experiments are given.

Mr. F. J. Jervis-Smith showed in 1897 that powdered carbon could be used in place of metallic filings in a coherer tube, and found it very sensitive. He employed graphitic carbon in a glass tube with pointed metallic electrodes, which could be screwed more or less into the carbon powder.[28] He states that placing the carbon powder in a vacuum does not improve it.

On the other hand, an iron or nickel filings coherer will not work well for long unless the filings are in a fairly good vacuum. The particles probably become too much oxidized on the surface.

In the latter part of 1897, Mr. F. J. Jervis-Smith, following Brown and Neilson, employed a combination of carbon coherer and telephone as a detector of electric waves. In 1898 he described the arrangement as follows :—

"A Hertz resonator is usually adjusted by altering the length of the two conductors on either side of the spark gap till the best results are obtained, this alteration of length has been effected by cutting off portions of the conductors, and observing the length of the spark in the gap in a dark room. Adjustment by means of this method is by no means easy, and when the primary oscillations are feeble, it is difficult to accomplish. In the new form of resonator, two ribbons of copper foil or a flexible metallic conductor of equal length are symmetrically coiled on to two cylinders, geared together by means of non-conducting cog-wheels; the cylinders are carried on insulated bearings, and the ribbons are kept in a state of tension by means of two weights attached to silk cords running over two pulleys; the length of the ribbons is regulated by the milled head."

These ribbons form extensions of metallic caps or ends to a small tube, which is filled with powdered carbon, in form of grains.

"This carbon detector also forms part of a circuit, including a telephone, and a battery and an adjustable resistance. To adjust the resonator, it is placed so

[28] See F. J. Jervis-Smith, *The Electrician*, 1897, vol. 40, p. 85, or *Science Abstracts*, vol. i. No. 166. Mr. A. A. C. Swinton (see *The Electrician*, 1897, vol. 40, p. 133), had previously noticed the reduction in resistance of a carbon tube filled with carbon granules by a neighbouring electric spark.

that it may be influenced by an oscillator or radiator of Hertz waves, the milled head is slowly turned until a clear, sharp click is heard by means of the telephone. Unlike the metal filings detector of Branly, this powdered carbon detector allows a very minute current to flow continuously through the telephone circuit, but when the carbon is subjected to a Hertz wave, a click is heard in the telephone."

T. Tommasina also constructed in 1899 a carbon coherer with carbon particles, which he says was as sensitive as a metallic filings coherer, and required less mechanical shock to decohere it. One efficient form consisted of two arc lamp carbons placed in a glass tube held by rubber stoppers, so that the ends were in light contact. He found this form of carbon coherer extremely sensitive, and not easily put out of order.[29] Mercury has also been used with great success in making coherers. T. Tommasina in 1899 made a coherer with a drop of mercury contained between two brass electrodes in a glass tube.[30] He does not say, however, whether it required tapping to make it decohere. It is a peculiar and valuable property of carbon in certain forms in combination with mercury and iron that it enables us to construct coherers which are self-restoring and return spontaneously and immediately to a high resistance condition after the impact of an electric wave.

As already mentioned, Professor D. E. Hughes in 1879 found that a carbon-steel microphone was sensitive to electric sparks at a distance, and he subsequently stated that he had at that time found it to be self-restoring. T. Tommasina discovered that a certain variety of graphitic carbon used in the microphones of certain Swiss telephones had the same property.[31] An interesting form of self-restoring cymoscope is one the invention of which has been attributed by Captain Quintino Bonomo to P. Castelli, a signalman in the Italian navy.[32] This coherer has been made in many forms, several varieties being described by Captain Bonomo in an official Report, published by him in 1902, in which he gave an account of work done in wireless telegraphy for the Italian Ministry of Marine between September, 1900, and May, 1901. In a glass tube of 3 mm. internal diameter are placed electrodes or rods of iron or carbon, fitting the tube closely, the ends of the iron or steel rods being well polished. If carbons rods are employed, it should be in the form used for arc lamp carbons with smooth ends. These rods nearly meet in the centre of the tube, and a drop of clean mercury is placed between them (see Fig. 12, Diagrams 1, 5, or 6). Alternatively there may be two drops of mercury with a short block of iron or carbon interposed between them (see Fig. 12, Diagrams 2, 3, or 4).[33] The size of the drop of mercury should be between 1·5 and 3 mm. in diameter. If less than 1·5 mm. the coherer is insensitive, if larger than 3 mm. it is not sharp in action. The distance between the electrodes of iron or carbon must be carefully adjusted. This is done by inclining the tube to 35° or 40° to the horizon, and displacing the upper electrode

[29] See *Comptes Rendus*, 1899, vol. 128, p. 666; also *Science Abstracts*, vol. ii. No. 1023.

[30] See *Comptes Rendus*, 1899, vol. 128, p. 1092; or *Science Abstracts*, vol. ii. p. 521.

[31] See T. Tommasina, *Comptes Rendus*, 1900, vol. 130, p. 904.

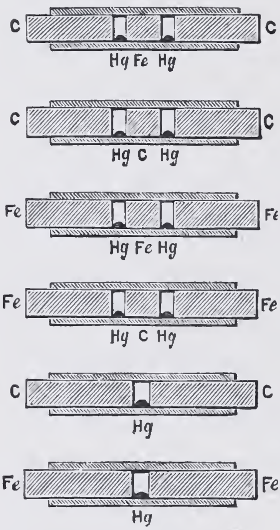
[32] See "Telegrafia Senza Fili," Rome, 1902; or *L'Elettricista*, ser. ii. vol. i. pp. 118, 173.

[33] See *The Electrical Review*, 1902, vol. 51, p. 968.

until there is a little space of 0·2 to 0·5 mm. between the mercury drop and the end of the upper electrode. The adjustment will then be correct when the tube is in a horizontal position.

The tube so prepared is placed in series with a single voltaic cell and a telephone, a resistance being added if necessary (see Fig. 13). When an electric wave falls on the tube, it causes a sudden decrease in the resistance between the electrodes, and a sharp click is heard in the telephone. The tube, however, if properly adjusted, returns immediately to its original high resistance. Hence if waves continue to arrive, the sound in the telephone is almost continuous.

In a slightly modified form, with one fixed plug or electrode of carbon, the other being an adjustable one of iron, and a globule of mercury included between (see Fig. 14) the inner ends, the arrangement was claimed in 1902 as the invention of Lieutenant Luigi Solari of the Italian navy, and denominated the Italian Navy Coherer.[34]



From "The Electrical Review."

Fig. 12.—Various Forms of Castelli Coherer.

The hygrometric state of the air is said to affect these tubes unfavourably if they are not sealed.

6. Restoration of Coherers to the Sensitive Condition. — The use of a metallic filings coherer made with most ordinary metals necessitates also the employment of some means for tapping the tube to restore it to the sensitive condition after the coherence has been produced. These mechanical shocks must be capable of very nice adjustment. In telegraphic work, the possibility of sending and receiving a *dash* signal as well as a *dot* signal on the Morse alphabetic code is essentially dependent upon this delicate setting of the tapper to administer a series of blows of just the right strength. The original clockwork tapper of Lodge is not sufficiently adjustable. The arrangements of Marconi, though admirable, require some dexterity to manage them. Inventors have therefore sought for simpler means of affecting the decoherence of the filings or surfaces, and also for forms of contact cymoscope which should be self-decohering or continually self-restoring to a sensitive condition.

H. Rupp found that rotating the metallic filings tube continually but slowly was sufficient to keep the filings in a sensitive condition.[35] T. Tommasina discovered that, when using coherers made with

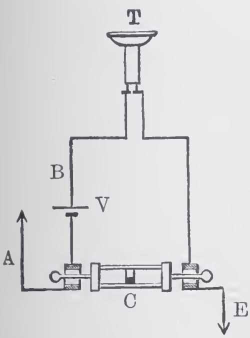
[34] See a letter to *The Times* of July 3, 1902, by the Marquis Luigi Solari, claiming this invention; also see a Royal Institution Friday Evening Discourse by Chevalier G. Marconi, June 13, 1902, reported in *The Electrician*, 1902, vol. 49, p. 490; also British Patent Specification, No. 18,105, of September, 1901, amended July 16, 1902, granted to G. Marconi, communicated by the Marchese Luigi Solari, for "Improvements in Coherers or Detectors for Electrical Waves."

[35] See H. Rupp, *Elektrotechnische Zeitschrift*, April 14, 1898; or *Electrical Review*, 1890, vol. 42, p. 535.

filings of magnetic metals, decoherence could be effected by a magnet placed a little distance above the tube. He accordingly fixed an electromagnet above a nickel, iron, or cobalt filings coherer, and caused the action of the electric wave on the tube to close the circuit of a single cell through the coherer and a relay. The relay in turn closed another cell circuit through the electromagnet, and so effected the decoherence. He says the arrangement worked perfectly.[36]

The explanation of this action seems to be that the chains of filings, which Tommasina contends are formed under the action of the waves, are torn apart.

Other inventors have attached the coherer to the armature of an electromagnet, the circuit of which included a voltaic cell, and was closed through a relay by the current sent from a separate cell through the coherer when the latter became conductive. The play



From "The Electrical Review."

Fig. 13. — Mode of employing a Mercury-iron-carbon Detector with a Telephone, T, and Auxiliary Cell, V, as an Electric Wave Detector.

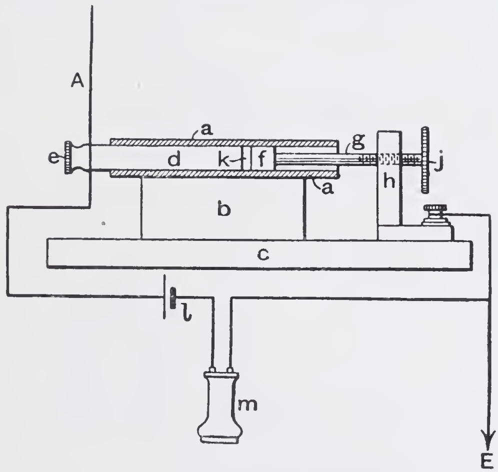


Fig. 14.—Italian Navy or Solari Coherer. A, antenna; E, earth connection; *d*, carbon plug; *f*, iron plug; *m*, telephone; *k*, mercury globule; *g*, adjusting screw; *l*, voltaic cell.

of the armature of the electromagnet can be limited by screw stops. The author has used for many years a device of this kind in a lecture apparatus, which was most easy to adjust and efficient in action. The form of coherer used was one suggested by the author some time ago.[37] It consisted of two L-shaped pieces of silver, *l*, which were bound on either side of a thin slip of ivory or fibre, *d*, in which a U-shaped gap was cut. This formed a small box, not more than 2 or 3 mm. wide, with metallic sides. In this box is placed a very small quantity of freshly made nickel filings, and the box is closed by a wooden wedge (see Fig. 15). This coherer is attached to the vibrating armature of an electromagnet, E, made like an electric bell, except

[36] See T. Tommasina, *Comptes Rendus*, 1899, vol. 128, p. 225; or *Science Abstracts*, vol. ii. No. 1166.

[37] See *Journal of the Institution of Electrical Engineers*, 1899, vol. 28, p. 292, remarks by J. A Fleming in "Discussion on Mr. Marconi's Paper on Wireless Telegraphy."

that two screw stops limited the play of the armature. The coherer is placed in series with a single dry cell and a relay which closes the circuit of another cell through the electromagnet above mentioned, and also closes another circuit of a large electric bell or Morse printing telegraphic instrument. When an electric wave falls on the coherer, the vibrating armature of the electromagnet gives one or two quick motions, and shakes the filings coherer back to a non-conductive condition.

7. Self-restoring Contact Detectors.—The disadvantage of all these arrangements from a telegraphic point of view is that the train of mechanism necessary to administer the shock to the coherer has so much mechanical and electrical inertia, and hence is limited in speed. Also, generally speaking, more than one blow must be applied. A series of light taps is more effective than one violent blow. All this means time, and therefore loss of speed in receiving signals.

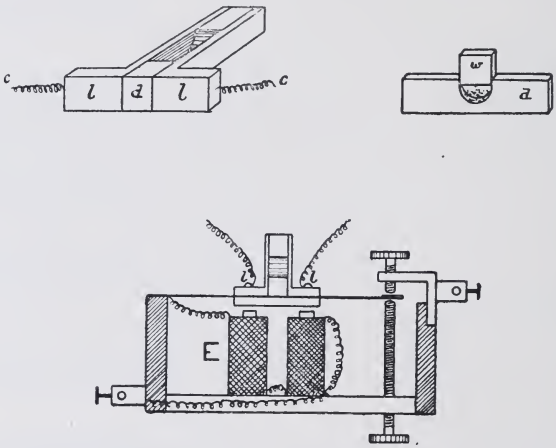


Fig. 15.—Fleming Coherer carried on the Armature of an Electromagnet.

Amongst other methods which have been tried is one due to Mr. S. G. Brown.[38] The pole pieces of the coherer tube are made of iron, and enveloped in magnetizing coils traversed by an alternating current. Between these pole pieces a small quantity of nickel or iron filings is placed, and under the action of an electric wave these loose filings cohere. The moment the wave ceases the alternating magnetism causes the filings to fall apart. Mr. Brown found that revolving a permanent magnet near an ordinary nickel or iron filings coherer tube had the same effect.

Of all these substitutes for tapping one of the most effective and simple is that due to Sir Oliver Lodge, Dr. Muirhead, and Mr. Robinson.[39] In this arrangement a steel disc is caused to revolve slowly by clockwork. The disc just touches a globule of mercury,

[38] See S. G. Brown, British Patent Specification, No. 19,710 of 1899.

[39] See Sir Oliver Lodge, "A New Form of Self-restoring Coherer," *Proc. Roy. Soc. Lond.*, 1903, vol. 71, p. 402; also British Patent of Lodge, Muirhead, and Robinson, No. 13,521 of June 14, 1902.

the surface of which is covered with a layer of paraffin oil (see Fig. 16). Under these conditions there is no good electric contact between the steel disc and the mercury. If a fraction of a volt difference of potential (0·3 of a volt or less) is created, by the use of a shunted voltaic cell between the steel and the mercury, then when an electric wave falls on this coherer the film of oil is perforated, and a current passes which is sufficient to work a syphon recorder placed in series with the cymoscope without the interposition of any relay. The rotation of the steel disc continually restores the cymoscope to a sensitive condition. The edge of the disc is continually kept clean by a pad of felt or leather.

An ingenious form of combined telephone and coherer has been designed by T. Tommasina. In this instrument the diaphragm of a Bell telephone carries on it a small carbon or metallic filings coherer, which is also in series with a bell and a relay. When the coherer become conductive it closes the circuit of the relay, and the latter in turn closes the circuit of another cell in series with the telephone coil. The jerk given to the vibrating diaphragm of the telephone resets the coherer. The arrangement works with more precision if the coherer contains iron or nickel filings, as then the magnetization of the telephone core assists the decoherence.

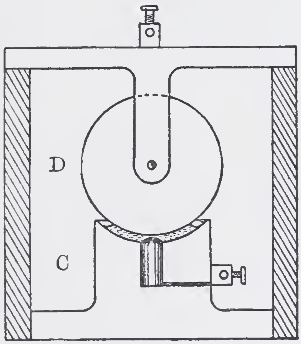


Fig. 16. — Lodge - Muirhead - Robinson Rotating Steel Disc Mercury Coherer. D, steel disc; C, cup containing mercury covered with oil.

All these arrangements, however, in which a sensitive relay is employed, involve continued adjustment and some considerable dexterity to obtain the best results. Hence of late years practice has tended in the direction of receiving arrangements which do not involve the use of an electromagnetic relay with a coherer, as this last method requires the employment of two sets of cells and a number of minute adjustments to secure uniformly good results.

Owing to the preference now given to methods of aural reception, many efforts have been made to find simple forms of contact detector capable of being used with a telephone which require no tapping, rotating, or other operations, but restore themselves immediately to their original state of resistance after the action of electric oscillations upon them. An example of this type is the tantalum detector of Mr. L. H. Walter.[40]

The construction of this detector is as follows: A platinum wire is sealed through the wall of a glass bulb and dips into a pool of mercury contained in it. A second platinum wire, also sealed through the glass, carries at its end a short length of tantalum wire which is part of a filament of a tantalum incandescent lamp. This wire is only 0·05 mm. in diameter, and just touches the mercury surface (see Fig. 17). The detector is used by joining the terminals of the tantalum

[40] See L. H. Walter, "On a Tantalum Wave Detector and its Application in Wireless Telegraphy and Telephony," *Proc. Roy. Soc. Lond.*, vol. 81, A, p. 1, 1908.

and mercury in series with a telephone, and with a potentiometer arrangement consisting of a shunted cell which applies a fraction of a volt 0·2 to 0·4 electromotive force in the circuit, so that the tantalum point is negative. The terminals of the detector are then also connected to the circuit in which oscillations are being set up. The arrangement employed in radiotelegraphy as a receiver with this detector is shown in Fig. 18, in which A is the antenna, S, P the oscillation transformer, C, C condensers. The tantalum detector has its electrodes joined across the terminals of the condenser. An electromotive force of about 0·3 of a volt is applied by means of a shunted voltaic cell B, and the battery circuit includes a telephone T. The inventor (*loc. cit.*) states that—

Detectors of this form have been tested at actual wireless telegraph stations, and it has been found that, while possibly not so sensitive for very weak oscillations (signals) as the electrolytic or magnetic detector, for slightly stronger oscillations the sound is *several times louder* than that obtained with the electrolytic, which is itself much more sensitive than the magnetic detector, and these results were obtained when each (the tantalum and the electrolytic) detector had the telephone most suitable for it. With the same telephones as are supplied

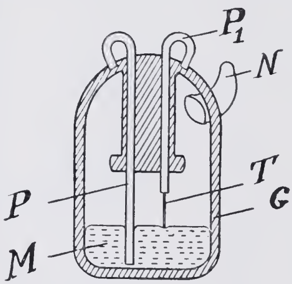


Fig. 17.—Walter's Tantalum detector. *P*, Platinum wire; *T*, Tantalum wire; *M*, Mercury; *G*, Glass vessel.

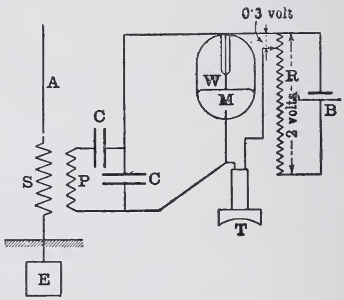


Fig. 18.—Arrangement of circuits employed in using the Walter Tantalum Detector as a Cymoscope in Radiotelegraphy.

with the "Telefunken" apparatus for use with the Schloemilch electrolytic detector, and consequently not so suitable for the tantalum detector, the signals obtained when the latter replaced a new Ferrié electrolytic detector were several times louder. (It is notoriously difficult to estimate telephonic sounds quantitatively, but the signals can be described as "good readable" and "loud" in the case of the electrolytic and the tantalum detectors respectively.) With the second detector made, very loud signals were obtained at a distance of 70 miles over sea, without any attempt at tuning, louder than those obtained with the electrolytic detector with the aid of a step-up oscillation transformer and careful tuning. Using one of the less satisfactory of the later models of the tantalum detector, loud commercial signals have also been obtained at a distance of 450 miles, the transmitter in this case not being one of the high-power stations, which are but poor tests, but an ordinary 2-kilowatt ship installation. The signals were in this case only slightly less loud when the tantalum detector replaced the electrolytic detector in the circuit, and since the very high resistance telephones used were not well suited to the tantalum detector, it is clear that the latter may be regarded as on practically an equal footing with the electrolytic detector, provided the signals are not too weak.

The apparent want of sensitiveness for very weak signals is due to the slight hissing sound which is normally present in all such imperfect contacts with mercury especially, though it is on a reduced scale as compared with the Italian navy coherer.

An examination of the tantalum detector by the resistance substitution method shows that in the receptive condition these have a fairly low resistance, 1200 to 1800 ohms (as compared with the filings coherer, 100,000 ohms or so; and the electrolytic detector, 30,000 to 50,000 ohms). This low resistance should prove beneficial to the tuning in certain cases. When oscillations are acting, the resistance drops to anything from 250 ohms for strong, to 70 ohms, say, for very strong signals. The great loudness of the signals obtainable with the tantalum detector is due to the large change in the current through the telephones. For this detector the ratio of the current when oscillations are acting to that in the normal condition ranges from 3 : 1 to 8 : 1 and can amount to 30 : 1 without reaching the maximum sound obtainable; the normal current, using 580-ohm telephones, is about $\frac{1}{20}$ to $\frac{1}{10}$ milliampere.

For the purpose of comparison the same ratio has been measured for a coherer of the Italian navy type. This gave a current ratio of 3 : 1 (about) as a maximum, above which it cohered permanently; it was more usually 3 : 2, at least in the author's experiments. The results with an electrolytic detector were not satisfactory, so that it is preferred to quote Reich's statement, that this ratio can easily reach 10 : 1.

It will thus be seen that the electrical behaviour of the tantalum detector approximates more to that of the electrolytic detector, as also does the sound.

Although the resistance of the tantalum detector is low, there is little likelihood of the point being damaged, for unlike the case of a solid metal-to-metal contact, a welding of the contacts is excluded, and no case has been observed in which it has been possible, with very powerful oscillations, to prevent the spontaneous return to the decohered state.

In his paper (*loc. cit.*) Mr. Walter also says—

The form of detector just described, while serving very well for use in fixed stations where a firm support can be obtained, is not so satisfactory when the detector is liable to be subjected to shaking or mechanical shocks during the reception of messages. Of existing forms of detector there are several which are rather sensitive in this way, and since a detector capable of withstanding rough usage may be useful in certain cases, it was thought desirable to find some method of immobilising the mercury while not interfering unduly with the sensitiveness to electrical stimuli or with the loudness of tone. Various devices have been tried without success, but one satisfactory solution is arrived at by constructing the detector in the following manner :—The tantalum wire is fastened in a platinum clip and the end of the tantalum encased in glass by a special method, necessitated by the impossibility of sealing in tantalum in the ordinary way as is done with platinum. The platinum wire is sealed into a minute glass bulb, B (see Fig. 19) blown on one end of a glass tube; the other end of the tube is connected to an air pump and the interior exhausted. The glass tube is next heated, when the vacuum causes it to collapse on to the tantalum wire. The end of the glass sheathed wire can then be ground down so that the tantalum surface is just flush with the glass (simply breaking off the glass end usually suffices). The mercury is contained in a glass tube, G, having a bore of $\frac{5}{32}$ inch. A larger tube would

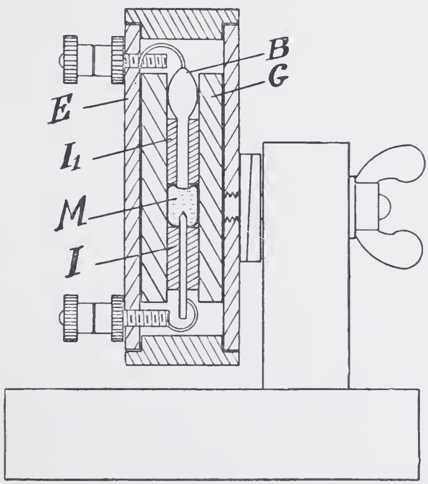


Fig. 19.—Walter's adjustable Tantalum Detector.

[*Figs.* 17 *and* 19 *are reproduced from the "Proceedings of the Royal Society" by permission of the Author and the Society.*]

be better, but the sensitiveness to shaking then reappears; a smaller tube gives a less sensitive and more variable detector. An ivory plug, I, through which a plantinum or nickel wire passes and projects, is placed at one end of a length of a few inches of such glass tube with thick walls. A few drops of mercury—enough to form a pellet, M, about $\frac{5}{16}$ inch long—are then put in and a second ivory plug, I_1, this one with the sheathed tantalum wire passing through it and projecting about $\frac{1}{20}$ inch, inserted so that the tantalum glass surface just dips into or under the mercury surface. The best (most sensitive) position is that shown in Fig. 18, with the glass tube vertical and the tantalum electrode at the top, and this gives a detector which may be roughly shaken or tapped during the reception of signals, without affecting their sound in any way. For sealing up, the whole arrangement is encased in an ebonite tube, E, and the ends filled in with insulating compound. The device is then permanent, though experience (time) is wanted to decide whether it is as inalterable as the first form.

8. Theories of Coherer Action.—At this point it is desirable to consider some of the theories which have been put forward to account for the phenomena of coherence under the impact of electromagnetic waves.

At an early stage Lodge advanced the opinion that the metallic surfaces in light contact were welded together, and his expressions have been interpreted to mean that he took the view that the action was in part, at least, a thermal one. The surfaces in loose contact, being at different potentials, were assumed to be drawn together and then autogeneously welded or caused to cohere, like clean surfaces of lead when strongly pressed together. Many observers have asserted that this process may be witnessed through the microscope, actually taking place. Thus D. van Gulik observed through the microscope the action of electric waves upon the rounded ends of two platinum wires almost in contact, and saw them drawn together when the wave fell on them. Also in another experiment he used mercury drops separated by a thin surface contamination of chalk, and said that he saw them coalesce under the action of radiation. Other observers assert that they have seen under the microscope minute sparks passing between the filings in a filings coherer when a wave was allowed to act on it. These observations may be correct as far as they go, but it is clear that very powerful radiation must have been employed, far in excess of that necessary to produce the true coherer phenomena.

Other physicists have examined particularly the filings coherer. T. Sundorph states that under the action of electric radiation chains of conducting particles are formed, and that the process may be examined by laying some iron filings on a glass plate between the ends of two rods. Then, on making electric sparks in proximity, some of the filings cling together and form connected chains from rod to rod. The loose or disconnected filings may be removed by a feeble magnet and the chains exposed to view.[41]

T. Tommasina supports this opinion, and says that these chains of particles stretching between the electrodes are more easily formed when the surrounding medium is distilled water or some dielectric other than air.[42]

[41] See *Wied Annalen*, 1899, vol. 68, p. 594; or *Science Abstracts*, vol. ii. No. 1717.

[42] See *Comptes Rendus*, 1899, vol. 129, p. 40; or *Science Abstracts*, vol. ii., No. 1718, 1899.

R. Malagoli, in referring to Tommasina's assertions, states that this process of the creation of chains of conducting particles between the electrodes can be witnessed in the case of brass filings placed between two plates of metal immersed in vaseline oil, when a difference of potential is made between the plates.[43]

In some of these experiments, however, considerable potential differences must have been employed. The actual electric or electromotive forces which come into play under the action of electric waves are very small, and experiments such as the above do not necessarily explain the real coherer effect.

E. Aschkinass very properly observes, moreover, that any theory of the coherer must take into account not only the coherence and increased conductivity of the magnetic and ordinary metals, but the decreased adherence and reduced conductivity which takes place between such substances as peroxide of lead, arsenic, potassium, etc. In other words, no theory of the coherer can be complete which does not include an explanation of the two kinds of effect on imperfect contacts discovered by Branly, which can be produced by an electric wave.[44]

Furthermore, we have to take into account that highly oxidized particles of metal operate in many cases as effectively in making a coherer as perfectly clean surfaces. Welding, in the ordinary sense of the word, cannot then occur.

The welding theory also fails to account for the power of carbon granules to form a good coherer, since carbon cannot be welded at any such temperature as can then exist at the points of contact of the carbon particles; and, moreover, the coherence is not permanent.

On the general subject of the sensitiveness of loose aggregations of metal filings to electric waves, the researches of Professor J. C. Bose are of particular interest.[45] He states that the sensitiveness of any form of contact cymoscope consisting of conducting particles depends upon the proper adjustment of the pressure between the particles and the value of the external electromotive force which is in waiting, so to speak, to send or increase the current through the contacts.

Bose discovered other substances which, like the peroxide of lead mentioned by Branly, exhibit the phenomenon of decreased coherence under the action of electric waves, such as metallic arsenic, potassium in petroleum oil, and some forms of silver. The best instance, however, of this so-called anti-coherer action is a light contact between a mass of compressed peroxide of lead and metallic lead.

S. G. Brown has made a so-called automatic *anti-coherer* by pressing lightly a lead point against a surface of lead which has been peroxidized. The electrical resistance of this contact becomes greater, and not less, under the action of electric waves, and it is also self-restoring. The fact can easily be shown as a lecture experiment.

Any theory of the action of electric waves or loose or imperfect

[43] See *Il Nuovo Cimento*, 1899, vol. 10, p. 979.

[44] See E. Aschkinass, "On the Coherer," *Wied. Ann. der Physik*, 1898, vol. 66, p. 284.

[45] See J. C. Bose, *Proc. Roy. Soc. Lond.*, 1899, vol. 65, p. 166; or *Science Abstracts*, vol. ii. No. 1716.

metallic contacts, to be complete, must embrace both the cases of coherence and those of increased resistance at the junction. It must explain why a copper wire lightly touching an oxidized copper wire experiences a great reduction in resistance at the contact when an electric wave falls upon it, whilst a lead wire lightly touching a peroxidized lead wire exhibits under the same conditions an increase in resistance at the contact.

Branly had recourse, therefore, to a theory in which the dielectric between the particles is considered to play an important part. He calls all the substances which when in light contact have their conductivity altered one way or the other by an electric wave, *radio-conductors*.

Guthe, however, gives reasons, derived from the experiments by himself and others, for doubting whether the interposed dielectric has the functions ascribed to it by Branly.[46]

J. C. Bose, after extensive examination of the coherer phenomena, divided all substances into positive and negative, the first and largest class reducing their resistance, and the second and smallest class increasing their resistance. He used the term *electric touch* to signify sensitiveness to electric radiation, and concluded that the effect of radiation was to produce a molecular change or allotropic modification of the substance acted upon, so that a positive substance becomes less positive, and a negative less negative; in some cases reversal taking place.[47] These descriptions, terms, and hypotheses have not, however, much increased our real insight into the matter.

It has been asserted that for every particular Branly tube there is a critical electromotive force in the neighbourhood of two or three volts, which causes the tube to break down and pass instantly from a non-conductor to a conductive condition, and that this critical electromotive force may become a measure of the utility of the tube for telegraphic purposes. Thus C. Kinsley (*Physical Review*, 1901, vol. 12, p. 177) made measurements of this supposed critical potential for different "coherers," and subsequently tested the same as receivers at a wireless telegraph station of the U.S.A. Signal Corps. The average of twenty-four experiments gave in one case 2·2 volts as the breaking down potential of one of these coherers or Branly tubes, 3·8 volts for a second, and 5·5 volts for the third. These same instruments tested as telegraphic cymoscopes showed that the first of the three was most sensitive.

On the other hand, W. H. Eccles (*Electrician*, 1901, vol. 47, pp. 682, 715) conducted some very instructive experiments with Marconi nickel-silver sensitive tubes, using a liquid potentiometer made with copper sulphate to apply the potential, so that the infinitesimal spark at the sliding contacts might be avoided, and the changes in potential made without any abruptness. He states that if the coherer tube is continually tapped at the rate of fifty vibrations per second, whilst at the same time an increase in potential is applied to its terminals, and the current passing through it measured on a

[46] See K. E. Guthe, "Coherer Action," paper read September, 1904, before the St. Louis International Electrical Congress; see also *The Electrician*, 1904, vol. 54, p. 92.

[47] See J. C. Bose, *Proc. Roy. Soc. Lond.*, 1900, vol. 66, p. 450.

galvanometer, there is no abrupt change in current at any point. He found that when the current and voltage were plotted against one another a regular curve was obtained, which after a time becomes linear. A decided change occurs in the conductivity of the mass of metallic filings when treated in this manner at voltages lower than the critical voltages obtained by previous methods. He ascertained that there was a complete correspondence between the sensitiveness of the tubes used as telegraphic instruments, and the form of the characteristic curve of current and voltage drawn by the above-described method.

In the same manner, K. Guthe and A. Trowbridge (*Physical Review*, 1900, vol. 2, p. 22) investigated the action of a simple ball coherer formed of half a dozen steel, lead, or phosphor-bronze balls in slight contact. They measured the current i passing through the series under the action of a difference of potential, v, between the ends, and found a relation which could be expressed in the form—

$$v = \mathrm{V}(1 - \epsilon^{-ki})$$

where v and k are constants.

The current through this ball coherer is, therefore, a logarithmic function of the potential difference between its ends of the form—

$$i = \frac{1}{k} \log \left(\frac{\mathrm{V}}{\mathrm{V} - v} \right)$$

and exhibits no discontinuity. The inference was drawn that the "resistance" is due to films of water adhering to the metallic particle, through which electrolytic action occurs. On the whole, the theory of a critical potential is not upheld by the general facts.

It is clear, however, that the agency which actually causes coherence is electromotive force, and that the matter to be explained is the reason electromotive force, acting on an imperfect contact, brings into better conducting contact the surfaces of certain materials which are in light or imperfect contact which constitute part of the circuit, whilst in a few other instances it is made worse. Lodge has shown that two conductors separated by a film of air one ten-thousandth of a millimetre in thickness, and having a difference of potential of 1 volt, are drawn together by electrostatic attraction with a force of 44 atmospheres per square centimetre of contact surface. Hence this pressure would be sufficient to force out a film of gaseous dielectric between the surfaces, and bring them into closer contact. Applying to this fact the electron theory, K. E. Guthe [48] has expressed the opinion that the electrostatic pressure is sufficient to bring the surfaces into such contact that electrons can pass over from mass to mass, thus establishing a current through the discontinuous substance. This theory, however, gives no explanation how it comes to pass that there is coherence in some cases and decoherence in others. Even if we grant that the passage over of electrons from one surface to the other brings the opposed surfaces to such a potential difference that a practical welding of them takes place, we have yet to explain why there should be such a marked contrast between the behaviour

[48] See paper on "Coherer Action," *loc. cit.*

of various substances, and why there should be such a difference between substances in the degree of mechanical shock necessary to rupture the contact thus formed.

On the whole, it cannot be said that our insight into the matter is very complete. Our knowledge of molecular processes is still far too imperfect to enable us to prescribe the actual atomic conditions at the surfaces of a loose contact between different pure or oxidized metallic masses.

The only facts which seem clear are that the phenomenon of coherence is essentially an electrical process, that it depends upon the creation of a small difference of potential between the surfaces in light contact, and as such is not directly an effect of radiation *per se*, but merely of the electromotive force set up when electric waves are incident upon the conductors in light contact, or upon others connected with them. That we have still much to learn concerning the general nature of the effect is shown particularly by the interesting facts observed by Schäfer.[49]

He described the following experiment :—

A very thin film of silver is deposited upon glass, and a strip of this silver is scratched across with a diamond, making a fine traverse cut or gap. If the resistance of this divided strip of silver is measured, it will not be found to be infinite, but may have a resistance as low as 40 or 50 ohms, if the strip is 30 mms. or so wide. On examining the cut in the strip with a microscope, it will be found that the edges are ragged, and that there are little particles of silver lying about in the gap. If, then, an electromotive force of 3 or 4 volts or so is put on the two separated parts of the strip, these little particles of silver fly to and fro like the pith balls in a familiar electrical experiment, and they convey electricity across from side to side. Hence a current passes having a magnitude of a few milliamperes. If, however, the strip is employed as a cymoscope, and connected at one end to the earth and at the other end to an aerial, then, when electric waves fall upon the aerial, the electrical oscillations thereby excited seem to have the property of stopping this dance of silver particles, and the resistance of the gap is much increased, but falls again when the wave impact ceases. If, therefore, a telephone and battery are connected between two portions of the strip, the variation of this battery current will affect the telephone in accordance with the waves which fall upon the aerial, and the arrangement becomes, therefore, a wave-detecting device. It is said to have been used in wireless telegraph experiments in Germany up to a distance of 95 kilometres.

A further study of these instances of *anti-coherence* or interruption of continuity is needed before we can possibly evolve a theory which will satisfactorily meet all the known facts concerning the effect of high frequency alternating electromotive force upon an imperfect or high resistance contact between substances of various kinds. It is possible that friction itself, generally speaking, is wholly an electric phenomenon.

There is a well-marked phenomenon of "fatigue" in the case of metallic filings coherers which also deserves mention and requires

[49] See E. Marx, *Phys. Zeitschrift*, vol. 2, p. 949; or *Science Abstracts*, vol. 4, p. 471; see also German Patent Specification, No. 191,663, Class 21a.

explanation. It has also been noticed that rise of temperature promotes or favours decoherence in the case of the positive class of radio-conductors.

It is clear that any theory of the operation of coherers must be in close touch with the theory of electric conduction generally. According to the electronic theory of electricity, the conduction of electricity in conductors is due to the motion of free corpuscles or electrons or so-called negative ions in them. In each conductor there is a certain number of these free ions in each unit of volume. It has been shown by Sir J. J. Thomson (see "Conduction of Electricity through Gases," p. 144) that an ion cannot fly off spontaneously and leave the conductor, since the moment it attempts to depart from the surface it is subjected to a force which is numerically equal to $\frac{e^2}{4d^2}$, where e is the ionic negative charge, viz. $3{\cdot}4 \times 10^{-10}$ electrostatic units, and d is the distance from the surface. Suppose, however, that two metal surfaces are very near together, and at a difference of potential of V volts, or $\frac{V}{300}$ electrostatic units. Let the distance between these surfaces be very small, and equal to x cms. Then the electric force in the interspace is $\frac{V}{300x}$ electrostatic units, and if this is comparable with or greater than $\frac{e^2}{4x^2}$, negative ions may be drawn out of one mass of metal and pass over to the other.

If, then, we have such a value of x and V that—

$$\frac{V_e}{300x} = \frac{e^2}{4x^2} \text{ or } x = 75\frac{e}{V}$$

this transference of ions can happen. Suppose that $V = 2$ volts, then the above equation is satisfied if $x = 5 \times 10^{-8}$. This is a distance comparable with atomic diameters. If, then, two metallic surfaces are in *close* contact, the creation of a certain small difference of potential between them will result in the passage of negative ions from one to the other, and therefore in electric conduction. Moreover, this transference will increase the potential difference, and this will operate to draw the surfaces still closer by electrostatic attraction. The phenomena of coherence between loose or imperfect contacts between metals can thus be explained on the electronic hypothesis, since when subjected to the action of an electric wave small differences of potential are created between the conductors in loose contact, owing to the electromotive forces set up by the wave in these conductors, or others to which they are connected. Where very great differences in conductivity exist between the two surfaces in contact, the action may result in an accumulation of negative ions at the bounding surface in such number as to stop the flow of a current across the junction, and thus explain the decreased conductivity of a junction between such substances as lead and peroxide of lead when traversed by electric oscillations.

In connection with the theory of coherers the reader may be referred to an interesting paper by Dr. W. H. Eccles, read before the

Physical Society of London, March 11, 1910, in which the author recounts experiments on coherers and a method of investigating them as follows:—

"A method of investigating detectors is developed with special reference to the relations between the energy given to the detector in the form of electrical vibrations and the energy delivered by the detector, as direct current, to the circuit of the indicating instrument. The stream of energy supplied to the detector was always of the same order as that usual in telegraphy. The detector under examination was placed in a circuit containing suitable inductance and capacity, which was secondary to a primary circuit. The primary could be set into electrical vibration by breaking a known current in it. The coupling was very small, so that when a current of a few millamperes was broken in the primary, the energy delivered to the detector was of the order a thousandth of an erg, and the electromotive force at the coherer terminals was of the order a tenth of a volt. The response of the detector was measured by comparing the sound in its telephone with the sound produced in the same telephone by interrupting a measurable direct current. A special switch key enabled the comparison to be made quickly. The power delivered to the detector and to the telephone was determined by extrapolation from measurements on stronger currents with the thermogalvanometer.

"The results of experiments on coherers made of oxidized iron wire dipping into mercury, and on coherers made of a clean iron point touching an oxidized iron plate, are exhibited as curves connecting: (1) the steadily applied E.M.F. and consequent current through the coherer; (2) the steadily applied E.M.F. and the power given to the telephone, for various rates of delivery of vibration energy to the detector; (3) the power delivered to the detector and the power passed to the telephone, the E.M.F. applied to the coherer being constant. Curves (1) show that in a self-restoring coherer the current increases more and more rapidly as the E.M.F. is raised, till, in general, a point of inflexion is reached, and then the current increases more slowly. Curves (2) show the rise and fall of sensitiveness to oscillations as the applied E.M.F. is increased. Curves (3) show that if W represents the power in watts delivered to the coherer, and w the power passed to the telephone circuit, then $w = m(\mathrm{W} - a)$, where m and a have values settled by the magnitude of the current through the detector. The quantity m for a good low resistance iron-mercury coherer has been found to be as high as 0·06; while a is usually near $1{\cdot}0 \times 10^{-8}$ watt. These curves show that these coherers are not 'voltage-operated' detectors, but 'integrating' detectors.

"The Author puts forward the hypothesis that the properties of an oxide coherer may arise solely from the temperature variations caused in the minute mass of oxide at the contact by the electrical oscillations and by the applied E.M.F. He examines the hypothesis mathematically, and shows that most of the phenomena recorded in the curves (1), (2), (3) above, can in this way be accounted for as perfectly as the present state of the measurement permits."

For details the reader is referred to the full paper.

9. Magnetic Detectors.—It was well known long before the middle of the last century that the discharge of a Leyden jar had a magnetizing power. Sir Humphry Davy magnetized sewing-needles with Leyden jar discharges in 1821. Joseph Henry, in the United States, between 1842 and 1850, explored many of the puzzling facts connected with this subject, and only obtained a clue to the anomalies when he realized that the discharge of a condenser through a low resistance circuit is oscillatory in nature.[50] Amongst other things, Henry noticed the power of condenser discharges to induce secondary currents which could magnetize steel needles even when a great distance separated the primary and secondary circuits. He employed

[50] See "The Scientific Writings" of Joseph Henry, vol. i. pp. 203, 293; also *Proceedings of the American Assoc. for Advancement of Science*, 1850, vol. iv. pp. 377, 378, Joseph Henry, "On the Phenomena of the Leyden Jar." The effect of the oscillatory discharge on a magnetized needle is clearly described in this paper.

this magnetization to test the direction of the secondary currents, and he was followed in the same field of research by Abria, Marianini, Riess, and Matteucci.

In 1870 Lord Rayleigh, in discussing some electromagnetic phenomena, pointed out that the resultant magnetic effect of an oscillatory discharge depends upon the direction of the maximum value of the current during the oscillation, and also that there may be superimposed magnetic effects in the same needle.[51]

In 1895 the subject was again taken up by Professor E. Rutherford, and in a very able paper, published in 1896, he described experiments he had made on the subject.[52]

It is a familiar fact that if a soft iron bar is magnetized and then removed from the field, it preserves, in virtue of retentivity, its magnetization after the magnetizing force is withdrawn. Also it is known that if the iron is pure and annealed, its coercivity is small, that is to say, a very small mechanical shock or twist is sufficient to destroy its magnetization. Physicists were also aware that discharges of a Leyden jar passed through the iron could act like mechanical shocks and remove the feebly held residual magnetization.

Rutherford found that electric oscillations sent through a coil surrounding a very small steel or iron needle which had been magnetized to saturation could more or less demagnetize it, and after examining with care the best conditions, he made a detector for electric oscillations as follows :—

About twenty pieces of fine steel wire 0·007 cm. in diameter, each about 1 cm. long, and insulated from each other by shellac varnish, formed the detector needle used. A fine copper wire insulated with silk was wound directly over the needle in two layers, and making in all eighty turns. As the solenoid was of very small diameter, about 15 cms. of wire served to wind the coil. This small detector was fixed at the end of a glass tube, which was itself fixed on a wooden base, the terminals of the detector coil being brought out to mercury cups. To the ends of this solenoid were attached two long rods which served as electric wave collectors, and in which the oscillations were set up. The detector needle was strongly magnetized and then placed inside the oscillation coil, and a small magnetic needle with attached mirror set up near its end. The residual magnetism in the bundle of steel wires caused a deflection of the magnetometer needle. Some distance away a Hertz oscillator was set up, and when this was in action the oscillations created in the receiver rods caused a partial demagnetization of the steel detector needle, and a corresponding deflection of the magnetometer needle. These experiments were conducted at Cambridge (England) in 1895, and Rutherford found he was able to affect the above described detector when the Hertz oscillator was at a distance of half a mile away across the town. Rutherford employed this magnetic detector for examining many

[51] See Lord Rayleigh (Hon. J. W. Strutt), "On Some Electromagnetic Phenomena," *Phil. Mag.*, ser. 4, vol. 38, p. 8; also *Phil. Mag.*, 1870, ser. 4, vol. 39, p. 431.

[52] Prof. E. Rutherford, "A Magnetic Detector of Electrical Waves and Some of its Applications," *Phil. Trans. Roy. Soc. Lond.*, 1897, vol. 189, A., p. 1; also *Proc. Roy. Soc. Lond.*, 1896, vol. 60, p. 184.

phenomena connected with electric oscillations, and in particular investigated by its aid the damping of electric oscillations as already described (see Chap. III. § 4).

In 1897 Professor E. Wilson took up the subject and constructed a detector consisting of a bundle of fine steel wires, wound over with two helices of insulated wire, one to convey the electric oscillations and the other to carry a magnetizing current. His object was to be able to remagnetize the detector by a battery current without removing it from its place, and he also patented an arrangement whereby the deflection of the magnetometer needle closed a circuit which remagnetized the detector needle and left it ready to detect another wave or oscillation.[53]

Success in these experiments depends upon attention to the details of construction of the detector needle. The steel wire used must be exceedingly thin. As the demagnetizing oscillations are very rapid, their magnetizing effect penetrates but a very little way into the mass of the metal, and therefore the proportion of the magnetism removed will be very small unless the wires are exceedingly thin. In the next place, the bundle must be short, so that the self-demagnetizing force is large, and under these conditions the residual magnetism is easily wiped out.

The effect observed is that due to the first oscillation, the magnetizing direction of which is such as to tend to annul the existing residual magnetization of the iron.

In 1902 Mr. Marconi described two other forms of magnetic cymoscope, one of which he has since used extensively for long-distance electric wave telegraphy.[54] These instruments depend upon the fact that when electric oscillations take place in a coil surrounding a bundle of iron or steel wires, they annul in part or in whole its magnetic hysteresis. The first form of detector described by Marconi is as follows: On a rod or core consisting of thin iron wires are wound one or two layers of thin insulated copper wire. On this winding insulating material is placed, and over this again another longer winding of insulated copper wire. The inner core is traversed by the electrical oscillations, and when used as a telegraphic cymoscope is connected in between the aerial wire and the earth.

The other coil is connected to a telephone. Near the ends of the core is placed a horseshoe permanent magnet, which is made to rotate slowly by clockwork (see Fig. 20). If then the inner coil is traversed by a train of electrical oscillations, the magnetic state of the iron-wire bundle is suddenly altered, and a sudden click or sound is heard in the telephone. If trains of oscillations are sent for longer or shorter periods, these sounds in the telephone run together into a continuous sound, and long and short sounds may be arranged into a code of audible signals on the Morse system.

Marconi found that a better and more convenient plan was one in which the iron moves and the magnet remains fixed. In this second arrangement (see Fig. 21) there are two wooden discs, *e*, *e*,

[53] See British Patent Specification, E. Wilson and C. J. Evans, No. 30,846 of 1897; also *The Electrician*, June 12, 1903, vol. 51, p. 330.

[54] See G. Marconi, "Note on Magnetic Detector of Electric Waves which can be employed as a Receiver in Space Telegraphy," *Proc. Roy. Soc. Lond.*, 1902, vol. 70, p. 341; or British Patent Specification, No. 10,245, of 1902.

grooved on the edge, and these are driven round slowly by clockwork. An endless band, *a*, made of a bundle of fine silk-covered iron wires, is arranged like a belt over these wooden pulleys, and the multifold iron band moves forward at the rate of 7 or 8 cms. per second. At one or more places the iron band passes through glass tubes, *g*, *b*. These are wound over with a coil of insulated wire, through which the electric oscillations pass, whilst over this is wound a longer coil of insulated wire, *c*, connected to a telephone, T. A pair of horseshoe magnets are placed with similar poles together opposite the last-mentioned coil.

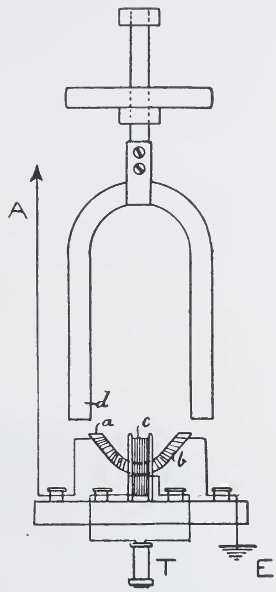


Fig. 20.—Marconi's Magnetic Cymoscope. (*First Form.*)

When the band is driven forward the portion of the band nearly opposite to the magnet poles becomes magnetized, but, owing to magnetic retentivity or hysteresis, that portion, in virtue of the motion of the band, is shifted forward in the direction of rotation, and is not therefore situated symmetrically with respect to the poles. If an electric oscillation passes through the oscillation coil, it annuls the hysteresis of the iron, and this magnetized portion slips back suddenly into a position exactly opposite to the magnetic poles. This amounts to moving a magnetic pole through the coil connected with the telephone, and it creates an induced current in this latter coil, and hence a sound in the telephone. The extreme sensitiveness of the telephone to induced currents bestows upon the whole apparatus a very great power of detecting feeble electrical oscillations. When used to detect electric waves, the oscillation coil is connected in between two aerial wires or between one aerial wire and the earth.

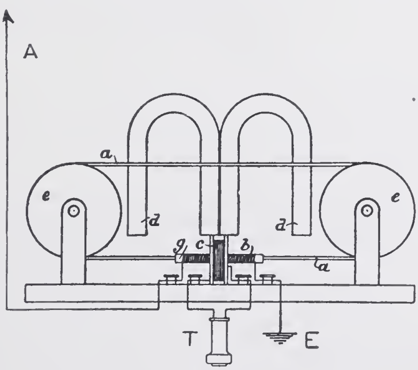


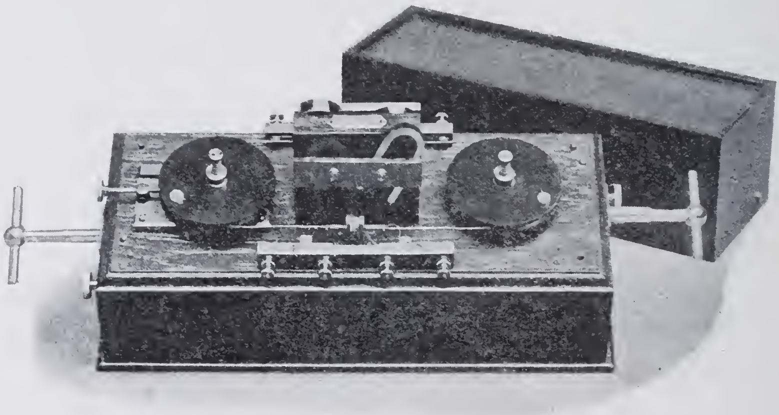
Fig. 21.—Marconi Magnetic Detector or Cymoscope. (*Second Form.*)

The sensitiveness of the instrument greatly depends upon the setting of the magnet. Several demagnetizing coils may be used on the same band of iron, each overwound with a telephone coil, and these latter may be joined in either series or parallel.

Mr. Marconi states that this magnetic detector is more sensitive and certain in its action and much more easy to adjust than any coherer, and more suitable for use in syntonic telegraphy.

Experience has shown that it is one of the most practical types of oscillation detector. It is easy to adjust, perfectly self-contained, and highly sensitive. Its invention was not only a stroke of genius, but involves as well a very interesting scientific principle. A view of the most recent form of this Marconi magnetic detector is shown in Fig. 22.

Professor E. Wilson [55] also constructed a magnetic detector, consisting of a bundle of iron wires carried through a cycle of alternately reversed magnetism by a periodic electric current. On this bundle was also wound a coil, through which the oscillations passed, and a third coil in series with a telephone. Owing to retentivity, the magnetic changes in the iron lag behind the magnetizing force. The action of the oscillatory field is to assist the magnetic



[By permission of Marconi's Wireless Telegraph Co., Ltd.

FIG. 22.—Marconi Magnetic Detector. Double-coil type.

changes when the magnetism is changing along the steep part of the cyclical curve, and this makes a change in the induction or flux linked with the secondary coil, and this, again, makes itself felt as a sound in the telephone.

The author has also devised a form of magnetic detector suitable for quantitative work, made as follows [56] :—

On a pasteboard tube, about 0·75 of an inch (18 mm.) in diameter and 5 or 6 inches long (15 cms.), are placed six bobbins of hard fibre, each of which contains about 6000 turns of No. 40 silk-covered copper wire (see Fig. 23*a*). These bobbins are joined in series, and form a well-insulated secondary coil, having a resistance of about 6000 ohms. In the interior of this tube are placed seven or eight small bundles of

[55] See Prof. E. Wilson, *British Association Report*, 1902; or *The Electrician*, vol. 49, p. 917, September 26, 1902; or British Patent Specification, No. 14,829, of 1902.

[56] See J. A. Fleming, "A Note on a Form of Magnetic Detector for Hertzian Waves adapted for Quantitative Work," *Proc. Roy. Soc. Lond.*, 1903, vol. 74, p. 398.

iron wire, each about 6 inches in length, each bundle being composed of eight wires, No. 26 S.W.G. in size, previously well paraffined or painted with shellac varnish. Each little bundle of iron is wound over uniformly with a magnetizing coil formed of No. 36 silk-covered copper wire in one layer, and over this, but separated from it by one or two layers of gutta-percha tissue, is wound a single layer of No. 26 wire, forming a demagnetizing coil. This last coil is in turn covered over with one or two layers of gutta-percha tissue (see Fig. 23*b*).

The magnetizing or inner coils are connected in series with one another, so that when a current passes through the whole of them, it magnetizes the whole of the wires in such a manner that contiguous ends have the same polarity. The outer or demagnetizing coils are

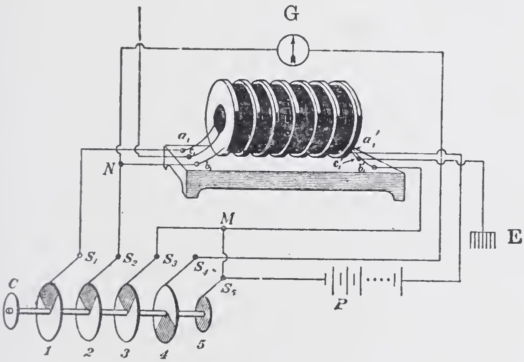
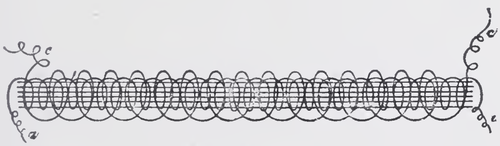


Fig. 23*a*.



From "The Electrical Magazine."

Fig. 23*b*.

Fleming Magnetic Cymoscope. Fig. 23*a*.—Bobbin, Cores, and Commutator. Fig. 23*b*.—A Single Iron Wire Core overwound with Magnetizing and Demagnetizing Solenoids.

joined in parallel. Associated with this induction coil is a rotating commutator, C, consisting of a number of hard fibre discs, secured on a steel shaft, which is rotated by an electric motor about 500 times a minute. There are four of these fibre discs, and each disc has let into its periphery a strip of brass, occupying a certain angle of the circumference. These wheels may be distinguished as Nos. 1, 2, 3, and 4. The brass sector of No. 1 occupies 95° of its circumference; the brass sectors of Nos. 2 and 3 occupy 135° of their circumference; and that of No. 4 disc 140° of its circumference. Four little springy brass brushes, S_1, S_2, S_3, S_4, make contact with the circumference of these wheels, and therefore serve to interrupt or make electric circuits as the disc revolves. The function of the disc No. 1 is to make and break the circuit of the magnetizing coils placed round the iron bundles,

and thus to magnetize them during a portion of one period of rotation of the discs and leave them magnetized during the remaining portion. The function of discs 2 and 3 is to short circuit the terminals of the secondary coils of the bobbin during the time that the magnetizing current is being applied by disc No. 1. A sensitive movable coil galvanometer, G, is employed in connection with the secondary coil, one terminal of the galvanometer being permanently connected to one terminal of the secondary coil, and the other terminal connected through the intermittent contact made by the disc No. 4. This disc No. 4 is so set that during the time that the secondary coil is short-circuited, and whilst the battery current is being applied to magnetize the iron-wire bundles, the galvanometer circuit is interrupted by the contact on disc No. 4.

The operations which go on during one complete revolution of the discs is as follows: First the magnetizing current of a battery of secondary cells is applied to magnetize the iron bundles, and during the time the terminals of the fine-wire secondary coil are short-circuited, and the galvanometer is disconnected. Shortly after the magnetizing current is interrupted, the secondary bobbin is unshort-circuited, and an instant afterwards the galvanometer circuit is completed, and remains completed during the remainder of one revolution. Hence, during a large part of one revolution, the iron-wire bundles are left magnetized, but the magnetizing current is stopped, and the galvanometer is connected to the secondary coil. If during this period an electrical oscillation is passed through the demagnetizing coils, an electromotive force is induced in the secondary bobbin by the demagnetization of the iron, and causes a deflection of the galvanometer coil. Since the interrupter discs are rotating very rapidly, if the electrical oscillation continues, these intermittent electromotive impulses produce the effect of a continuous current in the galvanometer circuit, resulting in a steady deflection, which is proportional to the demagnetizing force being applied to the iron, other things remaining equal. If the oscillation lasts only a very short time, the galvanometer will make a small deflection; but if the oscillation lasts for a longer time, then the galvanometer deflection is larger, and tends to become steady.

In the numerous experiments which finally resulted in the construction of the above-described form of wave detector, it was found to be essential to have the iron core in the form of a number of small bundles of iron wire, each wound over with its own magnetizing and demagnetizing coil. No good results could be obtained when the iron core was in the form of a large bundle, say half an inch in diameter, and enveloped by a single magnetizing and demagnetizing coil.

Another condition of success is the short-circuiting of the fine-wire secondary coil during passage of the current which effects the magnetization of the iron core. The core can be indefinitely increased in size, provided the augmentation of mass is obtained by multiplying small individual cores, each consisting of not more than eight or ten fine iron wires, and each wound over with a separate magnetizing and demagnetizing coil. The electromotive force in the secondary coil can in this manner be increased as much as is desired, and a very

sensitive electric wave detector suitable for quantitative work constructed. The commutator can be driven either by an electric motor or clockwork, or any other source of power.

This detector has been employed by V. Buscemi (see *Nuove Cimento*, February, 1905, vol. 9, p. 105) for quantitative measurements on the transparency of various dielectrics. An oscillator was placed in a metal box having a rectangular opening 35×40 mm. in size, and over this was placed a glass trough filled with various liquids to the depth of 6 mm. The following table shows the deflection of the galvanometer, which was connected to a Fleming magnetic cymoscope as above described :—

Liquid or dielectric in trough.	Galvanometer deflection in millimetres.
Air	21
Vaseline	22
Petroleum	16
Benzine	17
Æther	12
Sulphuric acid	0
Hydrochloric acid	0
Nitric acid	0
Distilled water	7
Sea water	0
Sodium chloride in water, 0·5 per cent. solution	1·5
Ditto, over 1 per cent. solution	0

Professor Wilson states [57] that Rutherford employed a moving band of iron wire in a magnetic detector in 1900 or 1901. Also, it has been asserted that Professor Fessenden, in the United States, was an early worker in this field of research.

From the above facts it will be seen that the magnetic detector in all its forms is essentially an alternating current ammeter. The coherer is primarily an electromotive force detector or voltmeter, because its action depends upon a difference of potential created between its terminals. The magnetic detector, on the other hand, is a current-affected instrument, and its proper position in an aerial or receiving circuit is at an antinode or place of current maximum.

A reduction in magnetic hysteresis does not invariably accompany the action of the electric oscillations on iron or steel. Walter and Ewing discovered that in hard steel an increase of hysteresis results when oscillations are sent through the metal. Their experiments were made with an apparatus, described below, in which a steadily revolving magnetic field tends to cause rotation in an iron or steel specimen suspended in it owing to the magnetic hysteresis. The torque so produced is resisted by the control of an elastic spring. When electric oscillations were passed through a closed coil of hard-drawn insulated steel wire, used as a specimen in such a manner, it was found that the hysteresis of the metal was increased, and that it tended to twist more in the direction of rotation of the magnet. We take the following description of their investigations from a paper read before the Royal Society.[58]

[57] See E. Wilson, " On Magnetic Detectors in Space Telegraphy," *Illustrated Scientific News*, August, 1903.

[58] See L. H. Walter and J. A. Ewing, *Proc. Roy. Soc. Lond.*, 1904, vol. 73 (p. 120).

"A small bobbin was wound with insulated soft iron wire, and the end soldered to the upper and lower halves of a spindle which was itself divided at the centre, the upper half bearing a controlling spring, and the lower dipping into mercury, from which a connection led to the other terminal. On passing oscillations through this winding a remarkable and unexpected result was obtained. The change of deflection was much more marked than in the former experiments, and was in the opposite sense indicating an increase of hysteresis while oscillations were present. Afterwards, hard steel wire was substituted for the soft iron, and a very great increase in the effect was observed, still in the same direction—that of increase of hysteresis.

"Owing to these encouraging results, it was decided to continue the experiments in this direction, abandoning the older form, in which a decrease of hysteresis was dealt with. The first bobbin constructed was about $\frac{5}{16}$ inch in external diameter, and had a vertical wire space of $\frac{1}{4}$ inch. The winding was a single No. 32-gauge iron wire, double cotton-covered, wound straight round from beginning to end. Later, No. 40 and No. 46 steel wires were employed, of which the latter gave the best results.

"It was soon noticed that any method of increasing the oscillatory current in the wires, as by winding the bobbin with two wires having a slightly unequal number of turns, was of advantage in giving a larger deflection. Later, a fine copper wire secondary, wound on the bobbin parallel to the magnetic wire, was tried, first with the ends insulated and then with the ends soldered together. A marked increase in deflection was observed when the secondary was closed, showing that the magnetic nature of the wire itself was influential. Accordingly, a bobbin was then wound with insulated steel wire, doubled back on itself. This non-inductive winding gave by far the best results hitherto attained, and is now used, except when special results are required.

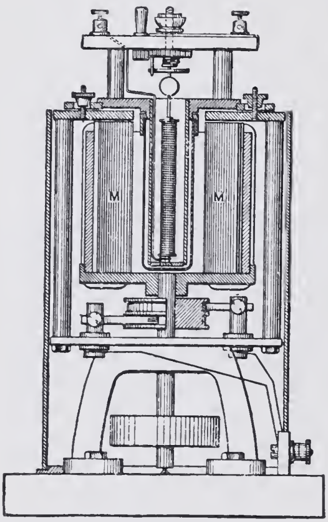


FIG. 24.—Walter and Ewing Magnetic Detector.

"The instrument, though described as a detector of electrical oscillations, may be said to measure rather than detect, giving quantitative as well as qualitative results, and being capable of regulation from a sensibility of the same order as that of an average coherer, down to practical insensibility to powerful sparks in the same room.

"In the instrument (see Fig. 24) the electro-magnet takes the form of a ring capable of moving round a vertical axis, and is provided on the interior with two long wedge-shaped pole pieces, M, M, the current to the winding being supplied through brushes bearing against insulated rings below. The magnet is made to revolve by an electro-motor, the best speed being about five to eight revolutions per second, but the electro-magnet may be replaced by a permanent magnet system giving a similar field. A structure is built up, external to the magnet, to support the vessel containing the pivoted bobbin and its centring arrangements. The bobbin itself is made of bone, and is about 2 inches long. It is provided with a still spindle at each end bearing in a jewelled hole, the two halves of the spindle being insulated from one another. The winding, which is, as far as possible, non-inductive, consists of about 500 turns of No. 46-gauge hard-drawn steel wire, insulated with silk. The bobbin is immersed in petroleum, or a mixture of petroleum with thicker mineral oil, which serves the double purpose of fortifying the insulation, and giving the damping effect necessary to steady the deflection due to the drag of the revolving magnet. Readings are taken by means of a spot of light, as with speaking mirror galvanometers, but a siphon-recording attachment has been fitted, and any form of contact for working a relay can be employed.

"The detector, as before mentioned, gives quantitative readings, and in some

cases the deflection may be too large to be easily read by the scale. For this purpose a variable shunt is provided, by which the deflection can be regulated.

"For the purpose of wireless telegraphy, the instrument has the advantage of giving metrical effects. The benefit of this in facilitating tuning, and in other respects, need not be insisted upon.

"From the physical point of view, the augmentation of hysteresis is interesting and unlooked for. It is probably to be ascribed to this, that the oscillatory circular magnetization facilitates the longitudinal magnetizing process, enabling the steel to take up a much larger magnetization at each reversal than it would otherwise take, and thus indirectly augmenting the hysteresis to such an extent that the direct influence of the oscillations in reducing it is overpowered. The net result appears to be dependent on two antagonistic influences, and, in fine steel wire, under the conditions of our experiment, the influence making for increased hysteresis, as a result of the increased range of magnetic induction, is much the more powerful."

10. References to Other Work on Magnetic Detectors.—Experiments have been made by A. L. Foley[59] to ascertain the effect of substituting other magnetic metals for iron in the Marconi form of magnetic detector. He found that nickel wires could be used in place of iron, and states that a mixed core or band composed partly of nickel and partly of iron wires acted better than one of either metal alone. Probably in view of the well-known fact that some varieties of tungsten steel possess very large hysteresis constants, it may be found that some iron alloys will do better for this purpose than pure iron wire, even if hardened. MM. H. T. Simon and M. Reich have made interesting experiments with a combination of magnetic wave detector and a Poulsen telegraphone.[60]

If a steel wire is uniformly magnetized by passing it over a magnetic pole, and if this wire is then sent through a short glass tube, on which is wound a coil of insulated wire, through which trains of electric oscillations are sent at intervals for a longer or shorter time, each train wipes out the magnetism of the iron wire in that part which is at the moment within the coil. Hence, if the wire passes uniformly through the coil we can, so to speak, obliterate the magnetism for long or short spaces, in accordance with the signals of the Morse alphabet, by so regulating the duration of the trains.

If this steel wire is then passed uniformly through the receiving or repeater part of a Poulsen Telegraphone, the listener in the attached telephone *hears* these signals as sounds in the telephone, and the wire becomes a record of the message, like the Morse tape of a printing telegraph.

Other investigations have also been made by M. C. Tissot, on forms of magnetic detector suitable for the detection of electrical oscillations. (See *Comptes Rendus*, 1903, vol. 136, p. 361; or *Science Abstracts*, 1904, vol. 7, A., p. 107.) Also we may note a paper by M. Maurain, on the "Suppression of Magnetic Hysteresis by the Action of an Oscillatory Magnetic Field" (*Comptes Rendus*, 1903, vol. 137, p. 917; or *Science Abstracts*, 1904, vol. 7, A., p. 108).

M. P. Duhem has also discussed the annulment of hysteresis by an

[59] See A. L. Foley, *Physical Review*, 1904, vol. 18, p. 349; also *Science Abstracts*, 1904, vol. 7, A., p. 460.

[60] See *Elektrotechnische Zeitschrift*, 1904, vol. 22, p. 180; or *Science Abstracts*, 1904, vol. 7, B., p. 426.

oscillatory magnetic field (*Comptes Rendus*, 1903, vol. 137, p. 1022; or *Science Abstracts*, 1904, vol. 74, p. 108).

A. Sella (*Accad. Lincei Atti*, 1903, vol. 12, p. 340; or *Science Abstracts*, 1904, vol. 7, A., p. 344) has noticed that electric oscillations can also annul the magnetic hysteresis due to deformation by twisting, or, as it is called, the magneto-elastic hysteresis.

A good general account of the various forms of magnetic detector which were devised up to 1905 was given by L. H. Walter in *Technics* for August, 1905, and also in the *Electrical Magazine* for December, 1905, vol. 4, p. 359.

Forms of magnetic detector for wireless telegraphy have been devised by Lee de Forest, Shoemaker and others, for descriptions of which the reader must consult the following United States Patent Specifications:—Lee de Forest, No. 772,878, June 20, 1903. This describes a magnetic detector with a divided core similar to the one previously described by the author (see p. 451).

H. Shoemaker, No. 711,182, September 5, 1902, and No. 734,476, January 8, 1903.

The theory of the magnetic detector in its various forms has been discussed by L. H. Walter,[61] W. H. Eccles,[62] J. Russell,[63] and C. Maurain,[64] and contributions to the discussion have also been made by Ascoli, Arnò, Piola, and P. Duhem.

Russell has carefully distinguished between the two conditions under which we can work.

(i.) Iron or steel may be placed in a constant magnetic field, and then subjected to the action of electric oscillations.

(ii.) Iron or steel may be subjected to continuing electric oscillations, and then the magnetic field around it changed.

In the case of Rutherford's experiment, hard iron or steel having considerable retentivity is subjected to a magnetic force, which is then removed, leaving remanent magnetization in the iron. The action of oscillations taking place round the iron is then always to remove or diminish this magnetization, and this can be detected by a change in the position of a suspended magnetic needle in the neighbourhood.

In Marconi's first form of magnetic detector, a horseshoe magnet is rotated slowly (about one turn in two seconds) over a thin bundle of hard iron wires, which are surrounded by two separate coils of wire. The iron is thus carried slowly through a cycle of magnetizing force of equal positive and negative values. The magnetization induced in the iron lags behind the magnetizing force in virtue of so-called hysteresis, and, therefore, if ordinates representing the magnetization are plotted out in terms of the magnetizing force as abscissæ, we obtain a magnetization curve of the well-known looped

[61] See L. H. Walter on "The Effect of Electric Oscillations on Magnetism," *The Electrician*, vol. 55, p. 83, 1905.

[62] W. H. Eccles, "The Effect of Electrical Oscillations on Iron in a Magnetic Field," *Proc. Phys. Soc. Lond.*, vol. 20, 1906, or *Phil. Mag.*, August, 1906.

[63] J. Russell, "Note on the Effect of Electric Oscillations on the Magnetic Properties of Iron," *Proc. Roy. Soc. Edin.*, vol. 26, p. 53, 1905–1906.

[64] C. Maurain, "Magnetic Detectors and the Effect of Electric Oscillations on Magnetism," *Journ. de Physique*, vol. 6, p. 25, 1907; or *Science Abstracts*, A., vol. 10, 1907, No. 479.

form. The area of this loop is proportional to the work expended in carrying the iron through one complete magnetic cycle. Russell states, as the result of his experiments, that if oscillations act continuously on the iron whilst it is being carried round the magnetic cycle, the area of this loop is greatly increased, thus showing an increase in hysteresis loss. If the oscillations come intermittently, as they would do in radiotelegraphic signalling, then the effect depends upon the particular point in the cycle at which the oscillations arrive. The result, in any case, is to produce a sudden change in the magnetization of the iron. Hence, if the oscillations are sent through one coil wound round the iron, the sudden change in magnetization produced by them creates induced or secondary electric currents in another coil wound over the oscillation coil, and therefore causes a sound in a telephone in series with the latter coil.

In Marconi's iron band form of magnetic detector the action is somewhat different. The band is passing through a magnetic field, so as to be always subject to a longitudinal magnetizing force, which is first in one direction and then is quickly reversed, because the two horseshoe magnets are placed with their poles near the wire and have similar poles in contact. Under these conditions, Russell found that the effect of a longitudinal oscillatory magnetic force is to increase the magnetization due to the steady force by an amount which is greater for an increasing than for a decreasing field. If the double north poles of the magnets are in the centre, and the iron moves from left to right, then the moving iron band distorts the field, and the effect of the oscillations passing round the iron is to increase the magnetization of the iron more on the left hand than on the right of the north poles. Both these effects alter the number of lines of magnetic flux through the secondary coil in series with the telephone, and therefore cause an induced current to flow through it, and the telephone in series emits a sound. Hence, Russell considers that Marconi's second form of magnetic detector acts in virtue of the increase of magnetization in iron which occurs when an oscillatory field is superimposed upon a slowly changing or stationary field near a cyclic extreme, whereas Rutherford's form of detector operates in virtue of a decrease of magnetization produced when the magnetizing force has been applied and has been removed.

The function of the moving band is twofold: it supplies the hard iron or steel in a condition of low permeability to be raised by the oscillations to a condition of higher permeability, and it distorts the field in the direction of motion. This view is rather different from that taken by Marconi himself and others, who have expressed the opinion that the action of the oscillations is to annul the hysteresis of the iron.

According to W. H. Eccles (*Phil. Mag.*, August, 1906), the effect produced when a bundle of iron wires is taken slowly round a magnetization cycle, and an oscillatory magnetizing force applied at any point, is to bring the iron back to the condition of magnetization it would have under the final steady impressed magnetic force acting on it if the hysteresis was suddenly annulled. The action of the oscillations is therefore to cause a return to the normal curve of magnetization.

In the Walter-Ewing form of detector we have different magnetic conditions. The field is then revolving somewhat rapidly, so that a drag is produced on the suspended iron, due to the so-called rotational hysteresis. Oscillations increase this hysteresis, and therefore the deflection of the suspended iron at least in fairly strong fields.

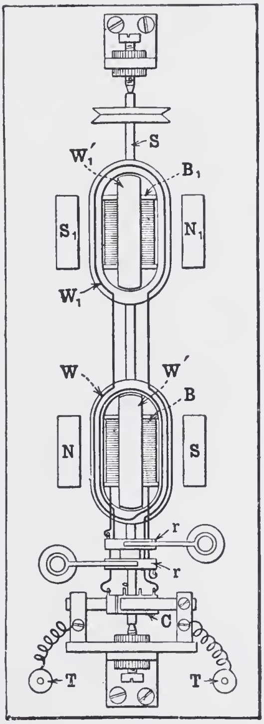
L. H. Walter considers that all magnetic detectors may be divided into two classes. First, those in which the oscillations act on the iron after the magnetizing force has been applied and withdrawn. Examples of this type are the original Rutherford detector and the Fleming quantitative detector above described. In this case the available energy is limited to the remanent magnetism in the core, and the action of the oscillations is to reduce or destroy this remanent magnetism. The second class, represented by Marconi's moving band detector, derive their energy from an external magnetic field and from the motive power driving the band, and the action of the oscillations is merely to release some of this energy. If the iron is moving through a field of increasing magnetic force, it is on the lower side of the hysteresis loop, and the action of the superimposed oscillatory field is to increase the magnetization when not actually at the peak of the curve, the increasing effect being, as E. Wilson first showed, greatest at or near the point of inflection of the lower branch of the hysteresis curve. This increase in magnetization of the portion of the iron band partly enclosed by the coil in series with the telephone creates the induced current in the latter. We may, therefore, in a sense, speak of this increase in local magnetization of the iron as due to an annulment of hysteresis. The action of the moving band detector is, however, essentially dependent on the supply of energy from an external source to magnetize the iron and move it against the magnetic force. The action of the oscillations is only a trigger action, which creates a sudden increase in the magnetic flux in a part of the iron embraced by the secondary or telephone coil. This causes in turn induced currents to flow through it, first one way and then the other. Accordingly, with the band detector, the only possible signal receiving instrument is a telephone, unless we provide some means of sifting out the direct from the inverse induced current in the telephone coil. This has been achieved, however, by means of one of the author's oscillation valves or glow-lamp detectors, described in a subsequent section, and by its use it is possible to obtain from a Marconi moving band magnetic detector, associated with a Fleming oscillation valve described in a subsequent section, intermittent but unidirectional currents, which can operate a relay, and therefore work any ordinary telegraphic printing instrument.

Another method has been devised by L. H. Walter,[65] by which a detector of the Walter-Ewing type, depending upon rotational hysteresis, can be made to furnish continuous currents. In this case oscillations are made to act on a magnetic mass undergoing reversals of magnetism in a rotating field in such a manner that the changes of magnetism produced by the oscillations create alternating induced currents in embracing coils of wire, which are rectified by

[65] See L. H. Walter, "On a Method of obtaining Continuous Currents from a Magnetic Detector of the Self-Restoring Type," *Proc. Roy. Soc. Lond.*, vol. 77, A., p. 538, 1906.

a commutator in the usual dynamo machine manner. The inventor has described his apparatus as follows:—

Two ebonite bobbins, B, B (see Fig. 25), mounted on the same spindle, are rotated in the field of two horseshoe permanent magnets, NS, NS, these bobbins being wound, in a similar manner to those illustrated in connection with the pivoted bobbin detector previously referred to, with some feet of steel wire of suitable resistance. A winding of two coils, W, W′, at right angles to one another, of a hundred turns, is placed on each bobbin at right angles to the plane of the steel wire winding, as in a drum armature, corresponding coils, *i.e.* W and W, W′ and W′, being connected in such a way that the E.M.F.'s generated are equal and opposite. The ends of the windings are connected to the segments of a four-part commutator, C. (For the sake of clearness, only one pair of corresponding windings, of one turn each, is shown connected in Fig. 25.) The steel wire windings of the two bobbins are exactly alike, the ends of one winding being insulated, while those of the other are connected to a pair of slip-rings, *r*, *r*, and brushes, by means of which the oscillations can be passed through the winding.



[*Reproduced from "The Electrician" by permission of the Proprietors.*

FIG. 25.

On testing this apparatus, with no oscillations acting, there was no potential difference at the brushes. On waves arriving, a steady deflection of the galvanometer was obtained in a direction corresponding to an increase of E.M.F. generated by the armature acted upon by the oscillations. By suitably proportioning the turns in the winding the sensibility was considerably increased. The usual speed employed is about five to eight revolutions per second. Higher speeds have been tried, and give a larger effect, but the zero is not so steady. Telephonic signals can, of course, be received simultaneously by connecting to the winding at some point before the E.M.F. is commutated. When a relay alone has to be actuated, however, it may be advantageous to so arrange matters that the generated E.M.F.'s do not exactly balance, and a small initial current, insufficient to actuate the relay, passes all the time through it. The change can be rapidly effected by a very slight shift of the brushes.

A further discussion of the action of electric oscillations upon magnetized iron has been given in another paper by J. Russell, in which he analyzes and compares the observations of W. H. Eccles and C. Maurain with his own, for which the reader must be referred to the original papers (see J. Russell, "The Shift of the Neutral Points due to Variation in the Intensity of Mechanical Vibrations or

Electric Oscillations superposed upon Cyclic Magnetization in Iron," *Proc. Roy. Soc. Edin.*, vol. 29, p. 1, 1908. Also J. Russell, "The Superposition of Mechanical Vibrations or Electric Oscillations upon Magnetization, and conversely in Iron, Steel, and Nickel," *Trans. Roy. Soc. Edin.*, vol. 45, p. 491, 1907). Very generally it may be said that the influence of electric oscillations upon magnetized iron is similar in effect to that due to mechanical vibration.

11. Electrolytic Oscillation Detectors. — A third class of detectors depend for their operation upon the power of electric oscillations to affect electrolytic conduction or the passage of currents through electrolytes when created by some independent and unidirectional electromotive force. One of the earliest observations on this matter was made in 1898, by A. Neugschwender.[66] He deposited on a sheet of glass a strip of silver, and divided it into two parts by a sharp cut about 0·3 mm. wide made with a razor. The two parts were then connected in series with a battery, telephone, and galvanometer. If the glass was dry no current passed, since the silver strip was cut in the middle. If a film of moisture was deposited on the glass, then a current passed, and the galvanometer deflected. Then, if electric waves fell upon an aerial wire or collecting wires connected to the two parts of the divided strip of silver, and set up oscillations across the gap, the galvanometer showed a sudden decrease in the current, and a sound was heard in the telephone.

The same phenomenon was investigated by E. Aschkinass (*Wied. Annalen*, vol. 67, p. 842) and by L. de Forest in 1899.[67] The latter found that tinfoil gave a better result than silver.

The above observers examined the effect through the microscope, and the latter saw the production of bridges or filaments of tin produced by electrolysis extend across the narrow gap. The operation of the oscillation seems to be to break up these "trees" or "bridges" of metal, and so suddenly reduce the current flowing across the gap.

Other oscillation-detecting devices have been invented which depend upon a similar action. One of these is that of De Forest and Smythe.[68] In this arrangement a tube, G, contains two small electrodes like plugs, which may be made of tin, silver, or nickel, or other metal. The ends of these plugs may be flat, and separated from each other by about $\frac{1}{200}$ inch. Sometimes the ends of these plugs are made cup-shaped, and the cup or recess filled with a mass of peroxide of lead and glycerine (see Fig. 26). In the interval between the electrodes is placed an electrolizable mixture which consists of glycerine or vaseline mixed with water or alcohol, and a small quantity of litharge and metallic filings. These metallic filings act as secondary electrodes. When a small electromotive force is applied to the terminals of the electrodes of this tube, through a very

[66] See "A New Wave Detector," A. Neugschwender, *Wied. Ann. der Physik*, 1899, vol. 67, p. 430; also *Science Abstracts*, 1899, vol. ii. p. 232; or German Patent Specification, No. 107,843 of December 13, 1898; or *Electrical Review*, May 26, 1899, vol. 41.

[67] See L. de Forest, "Electrolytic Receivers in Wireless Telegraphy." Paper read before the St. Louis International Electrical Congress, 1904. See also *The Electrician*, 1904, vol. 54, p. 94.

[68] See U.S.A. Patent Specifications, No. 716,000 and No. 716,334, applied for July 5, 1901. The equivalent British patent is No. 10,452 of May 6, 1902.

high resistance, R, of 20,000 or 30,000 ohms, a telephone being included in the circuit, an exceedingly small current passes through this mixture, and causes an electrolytic action which results in the production of chains of metallic particles connecting the two electrodes together. If, in addition to this battery circuit, one terminal or electrode of the cell is connected to an aerial wire, A, and the other terminal to the earth, E, then, on the arrival of an electric wave creating oscillations in the wire, these oscillations pass down into the electrolytic cell, where they break up the chains of metallic particles, and this interrupts the current passing through the telephone quite suddenly. This action is heard as a slight tick by an ear applied to the telephone. As soon as the wave ceases the chain of metallic particles is re-established, so that the appliance is always in a condition to be affected by a wave. This breaking up reformation of the chains of metallic particles is so rapid that a short spark made at the transmitting station is heard as a tick in the telephone, but a rapid succession of oscillatory sparks is heard as a short continuous sound; hence the two signals necessary for telegraphic conversation can be transmitted.

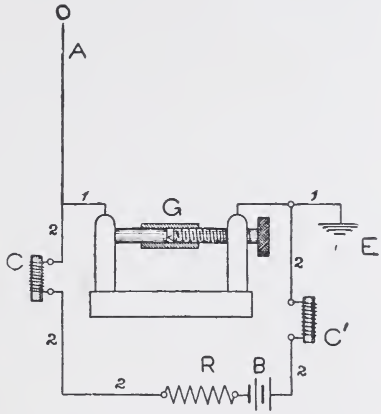


FIG. 26.—De Forest Electrolytic Detector.

A more important discovery of considerable interest in connection with this subject was due independently to R. A. Fessenden, Captain Ferrié and W. Schloemilch,[69] who found that electric oscillations had a marked effect on the voltaic polarization of carbon or metallic electrodes when in an electrolyte. A very short, fine, carbon filament, or very fine platinum wire, 0·001 mm. in diameter and 0·01 mm. long, is made the anode A in an electrolytic cell containing, say, dilute acid, the cathode K being a larger lead or platinum plate (see Fig. 27). This cell is placed in series with a shunted voltaic cell of slightly higher E.M.F. than the polarization cell, and a telephone is included in the circuit. The electromotive force of the shunted cell "polarizes" the electrodes of the electrolytic cell, and, in consequence of the deposit of oxygen gas upon the small carbon anode, the resistance of the cell increases so much that current through it is reduced nearly or quite to zero. If, then, the terminals of the electrolytic cell or detector are

[69] See Captain Ferrié, *Proceedings of the International Electrical Congress* (Paris, 1900), vol. ii. p. 289; see also W. Schloemilch, "A New Wave Detector for Wireless Telegraphy," *Elektrotechnische Zeitschrift*, 1903, vol. 24, p. 959; or *The Electrician*, 1903, vol. 52, p. 250. Fessenden described a detector in a United States Patent Specification, No. 12,115 of May 26, 1903, the original of which was No. 727,331 of May 5, 1903 consisting of a Wollaston wire or exceedingly fine platinum wire dipping a small depth into nitric acid, the vessel also containing another wire or electrode. He subsequently named this a liquid barretter. This patent application preceded the paper of Schloemilch.

connected to the two plates of a condenser inserted between two aerial wires or between one aerial wire and the earth, and electric waves allowed to fall on these collecting wires, the electric oscillations depolarize the surface of the carbon or platinum anode and suddenly reduces the resistance of the cell. If, therefore, a telephone is placed in series with the shunted battery and cell, the sudden increase in the current through it causes a sound to be heard in the telephone, and by the impact of long or short trains of waves, sound signals on the Morse code can be heard in the telephone.

Observations have been made on this cell by M. Reich, who substituted for the carbon a fine platinum wire made by the Wollaston process, the end of this wire just protruding from a glass tube into which it was sealed.[70] One theory concerning this action is that the cause of the phenomena is the annulment of the anodic polarization by the electric oscillations. Another view advanced by Fessenden is, that the action is thermal and due to a change in the resistance of

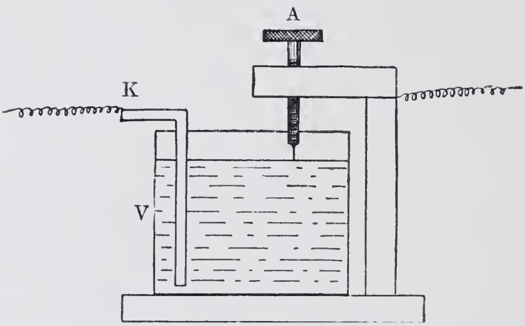


FIG. 27.—Fessenden or Schloemilch Electrolytic Detector.

that portion of the electrolyte near to the fine platinum wire (see § 11).

V. Rothmund and A. Lessing have conducted experiments with this electrolytic wave detector, using a platinum point electrode of 0·025 mm. in diameter and dilute sulphuric acid at its maximum conductivity as the electrolyte.[71] Their conclusions are that the effect is a depolarization action caused by the high frequency currents. The small size of the anode is no doubt a necessity owing to the small quantity of electricity which is conveyed by the oscillations.

The electrolytic detector resembles in its general construction a Wehnelt interrupter. In the former case, however, the operating current is a high frequency alternating current, and in the latter a continuous one. In both cases, however, we have two electrodes of very unequal surface, one a platinum point of very small surface, and the other a larger one of any other metal.

J. E. Ives has also investigated the electrolytic detector, and given some good reasons supporting the view that the action is due to

[70] See "Observations on the Schloemilch Wave Detector," by M. Reich, *Phys. Zeitschrift*, 1904, vol. 5, p. 238.

[71] *Annalen der Physik*, 1904, vol. 15, p. 193; or *Science Abstracts*, 1904, vol. 7, A., p. 896.

electrolytic polarization (see *Electrical World and Engineer*, New York, December 10, 1904). He employed an electrolyte having a zero temperature variation of resistance at 60° C., namely, a 2·5 per cent. solution of hypo-phosphorous acid. Below 60° C. the temperature coefficient is negative, and above it is positive. He found that the cell worked with this electrolyte. Also he deposited on the fine platinum anode platinum black. This deposit, as well known, reduces the polarization effect on platinum, and when the platinum wire was so treated the Schloemilch cell became inoperative. As the platinum black deposit could not interfere with any heating effect, this experiment strongly supports the view that the action is electrolytic.

The above-described electrolytic cell has also been claimed as the invention of F. K. Vreeland (see Poincaré and Vreeland, "Maxwell's Theory and Wireless Telegraphy," p. 188, 1904), who states that independently of Schloemilch, he found that a very minute anode of platinum wire, 0·0001 inch in diameter, placed in a cell containing nitric acid, together with a platinum cathode of larger surface, formed a very sensitive cymoscope far before an ordinary coherer.[72] It is to be noted that this last type of electrolytic detector will not operate unless the small surface is the anode, and that the resistance of the cell falls when electric oscillations act upon it, whereas the form of electrolytic detector described by De Forest increases in resistance by the action of electric waves.

Fessenden describes the production of the extremely fine platinum wire required as follows: A silver wire 0·1 inch in diameter has a core of platinum 0·002 inch in diameter. This silver wire is then drawn down to a diameter of 0·002 of an inch, and a short length of this wire is attached to the end of the screw A (see Fig. 28), which is capable of being screwed down into a vessel of nitric acid. If the silver wire is immersed for a small fraction of a millimetre, then the acid dissolves off the silver and leaves an extremely fine platinum electrode immersed. If this becomes destroyed, then all that is necessary is to screw down the silver wire a further length into the liquid, and thus prepare another fine electrode. The necessary electromotive force for the polarization of the fine electrode is applied by a dry Leclanché cell shunted with a high resistance and a sliding contact on this resistance for taking off a fraction of a volt as in Fig. 29.

A form of detector which is sometimes classified as an imperfect contact and at others as an electrolytic detector, is that invented by S. G. Brown. It consists of a pellet of peroxide of lead held between a plate of lead and one of platinum. If an external E.M.F. from a single secondary cell is impressed upon it so that

[72] It appears, however, from the judgment of Judge Wheeler in the United States Circuit Court given in the case of the National Electric Signalling Co. *v.* De Forest Wireless Telegraph Co., on October 16, 1905, that Vreeland was at the time of the invention an assistant to Fessenden and carrying out his directions. Priority in the invention of the electrolytic detector made as above described was therefore by this judgment awarded to Fessenden. In place of a silver-coated platinum wire immersed in nitric acid, it is also possible to use an iron-coated platinum wire produced by the Wollaston process which is immersed in dilute sulphuric acid, and in this case a silver cathode can be employed as in Fig. 28.

the current flows through the peroxide from platinum to lead, this current will experience a counter electromotive force due to the electro-chemical action of the lead-peroxide of lead-platinum couple. According to Mr. Brown, when oscillations pass through this couple they increase its counter-electromotive force by stimulating chemical

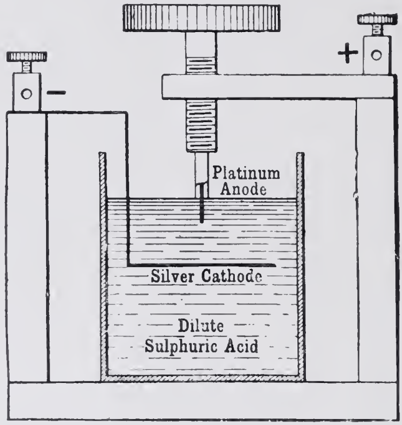


FIG. 28.

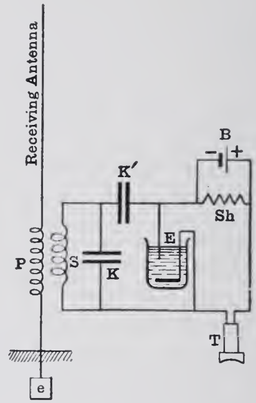


FIG. 29.

action and so reduce the current sent through it by the external cell. The couple acts, therefore, as a conductor of which the resistance is increased by electric oscillations. The pellet of peroxide is mounted up in a holder so as to apply to it an adjustable pressure (see Fig. 30), and is placed in series with a galvanometer and single cell. When

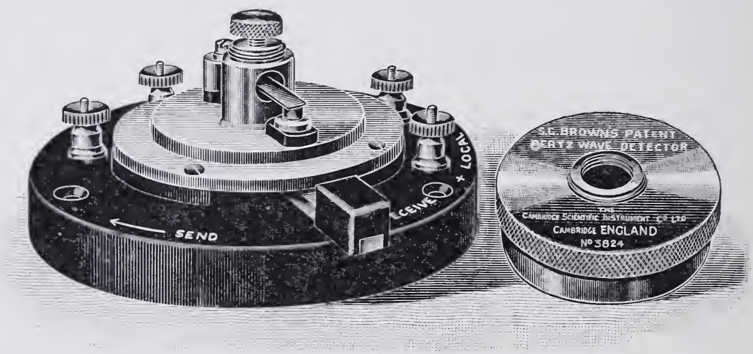


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FIG. 30.—S. G. Brown's Lead Peroxide Detector.

oscillations are created through the peroxide the deflection of the galvanometer decreases, but increases again when they cease.

12. **Thermal and Thermoelectric Detectors.**—Since electric waves give rise to electric oscillations when they fall in the right manner upon open wire circuits, and these oscillations are high frequency electric currents, we can employ them to heat some very fine high

resistance conductors and detect the wave by the heat it produces. In this case, however, we are measuring the *integral effect*, as German writers call it. The heat produced in a conductor by a train of decadent oscillations is proportional to the time-integral of the square of the instantaneous current value, and if we are employing an intermittent series of trains of oscillations it is proportional also to the number of trains of oscillations per second.

Hence thermal cymoscopes differ in this respect from coherers or magnetic detectors, in the operation of which the amplitude of the maximum voltage or current has an influence. No thermal wave detector has yet been invented which approaches in sensitiveness the best coherers, far less the magnetic or electrolytic detectors. An instrument in which heat is measured by the change in the resistance of a conductor produced by it is called a *bolometer*. The measurement of electric oscillations by the heat produced by them in a very fine wire is often called the *bolometric method* of detection. In this case some very fine high resistance wire, say, a wire of platinum, is made one arm of a Wheatstone's bridge, and its resistance is balanced against other conductors. In order to avoid the difficulties which arise from the heating of the bolometer wire by the bridge current, two similar wires must be placed in two arms of the bridge and a bifurcated arrangement employed, as shown in Fig. 16 of Chap. II. We can then obtain a steady balance in the usual manner and bring the bridge galvanometer to zero. If then electric oscillations are passed through one of the fine wires, it is still more heated, and its resistance increased, and the bridge balance is upset. Hence the bridge galvanometer deflects. In place of a Wheatstone's bridge a sensitive differential galvanometer may be employed, and a double fine wire. One wire is placed in circuit with each coil of the differential galvanometer and a balance obtained. If then electric oscillations are passed through one of the wires, its resistance is increased, and the needle of the differential galvanometer deflects. In place of the differential galvanometer we may employ a differential telephone, and thus make the arrangement more sensitive.

As far back as 1889 experiments were made to employ the heating power of oscillations set up by electric waves as a means of detecting them.

W. G. Gregory described a radiation meter to the Physical Society of London, in which the elongation of a wire on which electric waves impinged was rendered visible by the use of an Ayrton and Perry twisted strip and mirror.[73]

H. Rubens and R. Ritter in 1890 employed a bolometric instrument in researches on electric gratings (see *Wied. Annalen*, vol. 40, p. 56, "Ueber das Verhalten von Drahtgittern gegen Electrische Schwingungen"). The details of their bolometer were as follows: Two rectangles, R and S, of fine iron wire 0·07 mm. in diameter were employed (see Fig. 31). These were made the arms of a Wheatstone's bridge arrangement of conductors. One of these rectangles was connected with a linear oscillator, or antenna, A, which acted as a receiving wire, and when electric oscillations were set up in A by the impact on it of electric waves, these caused the circuits of the rectangle

[73] *Proc. Phys. Soc. Lond.*, 1889, vol. x. p. 290.

R to become heated, and so upset the balance of the Wheatstone's bridge. The deflection of the galvanometer G served then to detect and measure the electric radiation falling on the receiving wires.

C. V. Boys and W. Watson also gave an account, in 1890, of experiments made by them to measure electromagnetic radiation by means of the heat created by electric oscillations set up by it in linear conductors.[74]

C. Tissot has particularly studied the use of a bolometer for detecting electric waves at great distances from the source.[75] He employs an exceedingly fine platinum wire of great purity, the diameter of which is not more than 10 or 20 microns (1 micron = 0·001 millimetre). This wire is used in the arms of a bridge arrangement similar to that of Rubens and Ritter. With such a bolometer wire,

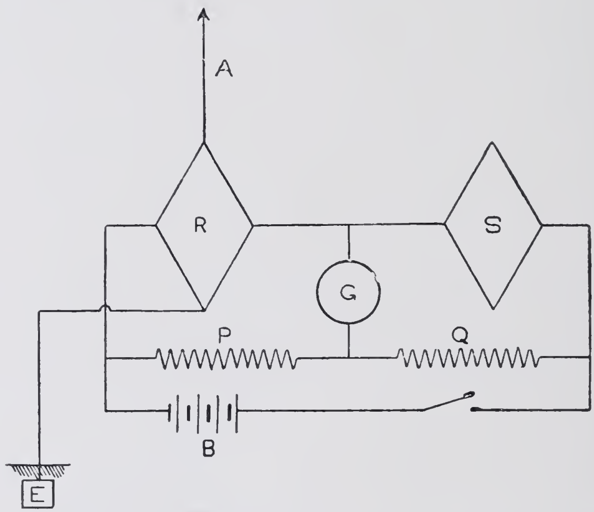


FIG. 31.—Bolometer Cymoscope. R, S, rectangles of fine wire forming a Wheatstone's bridge, with resistances, P and Q.

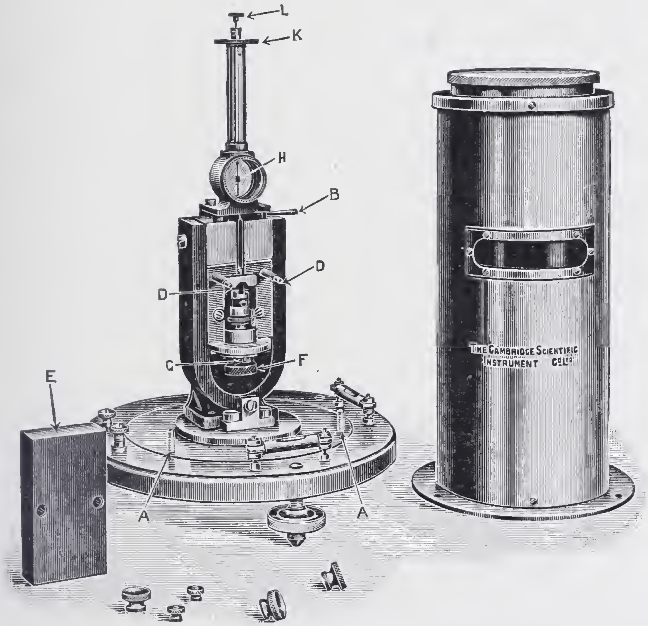
he states that he has detected electric waves at a distance of 50 kilometres from the radiator when using the arrangements required for electric wave wireless telegraphy.[76]

W. Duddell devised in 1904 a thermal instrument of great sensibility for detecting electric oscillations.[77] He employs a form of Boys' microradiometer, in which a delicate thermocouple is suspended by a quartz fibre in a strong magnetic field. An attached mirror enables deflections to be estimated (see Fig. 32). Underneath this thermocouple he places a very thin and narrow strip of metal (gold leaf),

[74] See *Proc. Phys. Soc. Lond.*, 1890, vol. xi. p. 20.
[75] C. Tissot, "Bolometers as Detectors of Electric Waves," *Journal de Physique*, 1904, vol. 3, p. 324; also *Science Abstracts*, 1904, vol. 7, A., p. 700.
[76] See C. Tissot, *Comptes Rendus*, 1904, vol. 137, p. 846; or *Science Abstracts*, 1904, vol. 7, A., p. 100.
[77] See W. Duddell, "Instruments for Measuring Alternating Currents," *Phil. Mag.*, 1904, vol. 8, p. 91. See also Chap. II. p. 197, of this book.

through which the electric oscillations are passed. These oscillations heat the strip feebly. One junction of the small suspended thermocouple rests just above the strip but not quite touching it, and is therefore heated by radiation and convection. The couple is therefore traversed by a current, and is deflected in the magnetic field. If an ordinary Bell telephone is connected in series with the strip and a sound uttered to it, the alternating current so produced heats the strip sufficiently to make a large deflection of the ray of light reflected from the mirror attached to the thermocouple.

If the thin strip is placed in series with a pair of long rods or between an aerial wire and the earth, and if electric waves fall on



[*From the Cambridge Scientific Instrument Company.*

FIG. 32.—Duddell Thermo-galvanometer for measuring Very Small Alternating Electric Currents.

these wires, then the electric oscillations set up heat the strip, and the instrument becomes a thermal cymoscope.

R. A. Fessenden has described the construction of a thermal electric wave detector made as follows [78] :—

An extremely fine platinum wire, about 0·003 inch in diameter, is embedded in the middle of a silver wire, about $\frac{1}{10}$ inch in diameter, like the wick of a candle. This compound wire is then drawn down until the diameter of the silver wire is only 0·002 inch, and hence the platinum wire in its interior, being reduced in the same ratio, will have been drawn down to a diameter of 0·00006 inch. A short piece

[78] See U.S.A. Patent Specifications, No. 706,742 and No. 706,744, applications of June 6, 1902.

of this drawn-down wire is then bent into a loop and the ends fixed to wires. The tip of the loop is then immersed in nitric acid, and then dissolved in the silver, leaving an exquisitely fine platinum wire loop, W, a few hundreds of an inch in length and having a resistance of about 30 ohms (see Fig. 33). This little loop is sealed into a glass bulb, A, like a very small incandescent lamp, or it may be enclosed in a small silver bulb, and the air may be exhausted. If an electrical oscillation is sent through this exceedingly fine platinum wire it heats it, and rapidly increases its resistance. The electrical oscillations produced in an aerial are sent through a number of these loops arranged in parallel, and the loops are short-circuited by a telephone, joined in series with a source of very small electromotive force produced by shunting a single cell, or opposing to one another two cells of nearly equal electromotive force. Any variation of resistance of the little platinum loops due to the heat produced by the oscillations, by suddenly altering the current flowing through the telephone, will cause a sound to be heard in it. The electrical oscillations, when passing through the loops, are therefore detected by the heat which they generate in these exquisitively fine platinum wires.

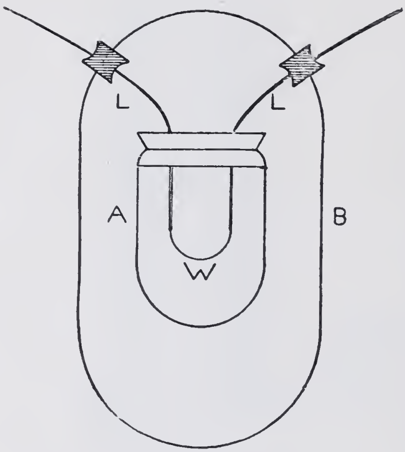


Fig. 33.—Fessenden's Thermal Detector.

Since the action essentially depends upon a variation of resistance with rise of temperature, and since many electrolytes or conducting liquids have a far greater temperature coefficient than metals, it is obvious that it must be of advantage to employ a liquid in place of a metallic wire. If a tube with an extremely small bore is filled with a suitable electrolyte, it can take the place of the platinum wire in the above-described thermal receiver. Fessenden calls this arrangement a "liquid barretter."[79] The liquid column has another great advantage over the fine wire, in that whilst the wire may be fused by an excess of currents, the liquid column always restores itself to continuity.

Fessenden found that there was no necessity to include the liquid in a tube. He discovered that if an extremely fine platinum wire, such as he used in his earliest form of thermal cymoscope (see Fig. 33), was broken whilst it was immersed in a conducting liquid, such as nitric acid, it nevertheless continued to act as efficiently as before, hence he constructed a "liquid barretter," which is in fact the electrolytic detector described in the previous section, in the following manner: It consists of two thin platinum wires immersed in a little

[79] See U.S.A. Patent Specification, No. 731,029, application of May 4, 1903; also reissued U.S.A. Patent, No. 12,115, dated May 26, 1903.

vessel containing a suitable liquid. The immersion of the ends of the wires is such that an electrical contact takes place between the liquid and the wires, or the vessel may be divided into two parts by a glass partition, having an exceedingly small hole in the centre 0·003 inch in diameter. The diaphragm is so arranged that one electrode wire is on one side of the partition and the other on the other; hence we have two masses of liquid which are virtually connected by an extremely small tube or liquid. It follows from well-known electrical laws that if an extremely fine wire is immersed in a liquid to a very small extent all the temperature effects will be local, and will take place inside of a certain sphere of a small radius. Thus, for example, if a platinum wire having a diameter 0·0004 inch is immersed in nitric acid to a depth of 0·00002 inch, practically all the temperature effects will be localized, and will take place inside a sphere the radius of which will be 0·0004 inch.

It is found that certain liquids act better than others. For example, although a solution of carbonate of soda, caustic soda, nitrate of potash, and other electrolytes give good results, Fessenden found it was better to use nitric acid, because the effects are stronger than with most other liquids. He constructed the extremely fine platinum wire by coating a wire of platinum of sensible thickness with a thick layer of silver and then drawing down the two together; the silver is then dissolved off for a certain small length by nitric acid, and leaves an extremely fine fibre of platinum immersed in the nitric acid. If such a liquid barretter is placed in a circuit in which electric oscillations are taking place, the liquid and the fine electrode become heated during the passage of the oscillations, and the resistance, therefore, is varied suddenly, and this can be detected by placing in series with the liquid cell a telephone and a voltaic cell and resistance so adjusted as to send a small current through the electrolytic cell. It has already been pointed out in describing this electrolytic detector that the action may be, and probably is, electrolytic, and due to annulment of polarization rather than to a purely thermal action.

Instead of making the change in resistance of a fine wire detect the oscillations, we may detect a very small rise in temperature in it by placing in contact with the wire a thermojunction. Such an arrangement was first employed by Klemencic in 1891.[80] The oscillations are sent through a fine constantan wire, and against this rests a thermoelectric couple of iron and constantan or other suitable metals. The ends of the couple are connected to a low resistance galvanometer. When a train of oscillations are passed through the fine wire they heat it, and the galvanometer connected to the thermocouple indicates the rise of temperature.

An improved arrangement of this kind was devised by the author in 1906, taking advantage of the position of tellurium and bismuth in the thermoelectric series, and also of the fact that such a fine wire rises to a higher temperature by the passage of a given current when placed in a high vacuum. A double glass test-tube, similar to a Dewar vacuum vessel, was constructed (see Fig. 34), the space between the two tubes being subsequently exhausted. Through the bottom of the

[80] See J. Klemencic, *Wied. Annalen*, vol. 42, p. 417, 1891.

inner test-tube were sealed four wires; two of these, *a*, *b*, were connected to a fine constantan wire, and the other two, *c*, *d*, were connected to a tellurium-bismuth thermojunction, T, formed of very fine wires of bismuth and tellurium, the junction being soldered by a special solder to the centre of the constantan wire. A high vacuum was then made in the interior space. When oscillations are passed through the constantan wire, a suitable low resistance galvanometer, G, being connected to the leads from the thermojunction, the galvanometer deflects, the deflection being proportional to the square of the integral value of the oscillations.

The inclusion of the thermocouple and heater wire in a very high vacuum has a great effect in increasing the sensibility. It has been noted, both by the author and by P. Lebedew,[81] that for couples and wires of bright or polished metal the sensitiveness may be increased by so doing as much as 25 times. This great increase, however, takes place chiefly between a reduction of air pressure from 0·1 mm. to 0·0001 mm., and for much lower pressures there is hardly any change. A pressure of 0·01 mm. is sufficient to give almost the best effects (see Fig. 35).

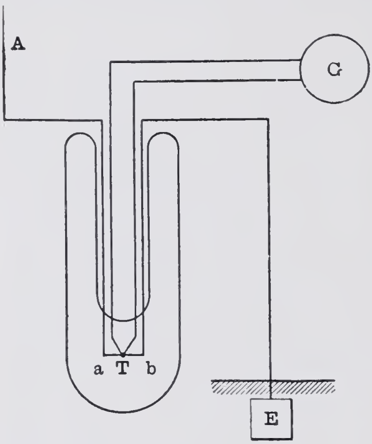


FIG. 34.—Fleming Thermoelectric Hot-wire Microammeter.

The advantage of such a detector is the ease with which it can be calibrated by means of a known continuous current passed through the fine wire. For if we pass any train of oscillations which gives on the galvanometer the same deflection as a certain direct current, we know that the mean-square value of those oscillations must have the same ampere value as the unidirectional current which is thermally equivalent to them. It has been found, however, that it is not necessary to pass the oscillations through a wire. If pieces of two metals selected at opposite ends of the thermoelectric series are pressed in contact at one point, and if stout connecting wires make good contact with these pieces of metal at some other point, then, when oscillations are passed through the contact point, they produce heat there, and therefore excite a thermoelectromotive force. If, then, such a junction is inserted in an oscillatory circuit, and also has the terminals of a telephone connected to its leading-in wires, the telephone will respond by a sound to each passage of a train of oscillations. It is necessary, however, that the materials selected for the couple should have poor thermal conductivity, so that the heat generated at the small surface contact shall be localized there and not be conducted to the other junctions. L. W. Austin has described such thermoelectric detectors made with tellurium and

[81] See P. Lebedew, *Ann. de Physik*, vol. 9, 1902; or *The Electrician*, October 3, 1902, p. 952.

aluminium and tellurium and silicon.[82] In constructing it, a bead of tellurium fused on the end of a springy brass wire is adjusted so as to press more or less tightly against an aluminium wire or disc. The couple, having a high resistance, is inserted as a shunt across the plates of a condenser in the receiving circuit, and a high resistance telephone is connected to the elements of the thermo-couple. The question has been raised whether the action of this detector does depend upon a true thermoelectromotive force created by the heat produced at the small surface contact. The action as an oscillation detector may equally well be accounted for by the power which certain junctions, certain metals and non-metals, possess

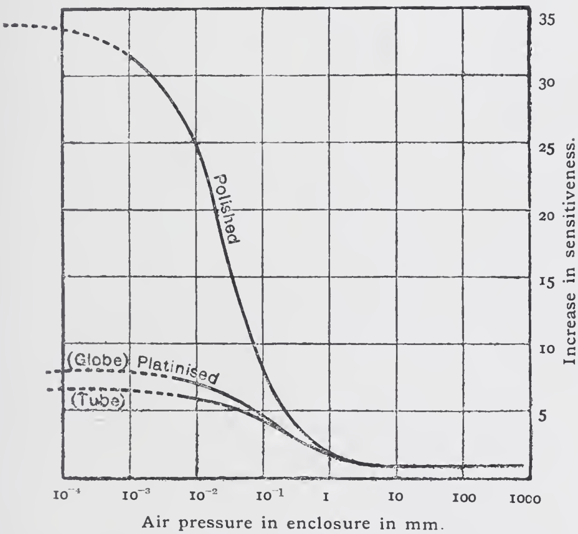


FIG. 35.—Curves showing the Increase in Sensitiveness of a Thermal Ammeter by enclosure in a space with reduced Air Pressure.

of rectifying a high frequency current. In other words, such junctions possess a unilateral conductivity.

13. Rectifying Detectors.—It has been found that a contact of small surface between certain conductors, as, for instance, between tellurium and aluminium, also between silicon and copper, and carbon and steel, possesses the power of rectifying high frequency alternating currents.

Thus, if a copper or steel point is pressed against a piece of silicon it was found by G. W. Pickard that this contact will act as an oscillation detector when shunted by a telephone.[83]

W. L. Austin investigated the behaviour of a silicon-steel junction of this kind, and found that an electromotive force of 2·5 volts could

[82] See W. L. Austin, "On a High Resistance Contact Thermoelectric Detector for Electric Waves," *Physical Review*, vol. 24, p. 508, 1907.

[83] See G. W. Pickard, *Electrical World of New York*, vol. 48, p. 1003, 1906.

pass a current of $25{,}000 \times 10^{-6}$ amps. from steel to silicon across the junction, but only a current of 6000×10^{-6} amps. in the opposite direction.[84] It follows, therefore, that such a junction rectifies an alternating current, and Austin has shown that when a steel-silicon junction is placed in series with an ordinary direct current galvanometer, electric oscillations acting on that circuit are rectified, and deflect the galvanometer. For small alternating voltages below about 0·2 of a volt, the rectified currents are proportional to the square of the alternating voltage. That this effect is not a pure thermoelectric effect is shown by the fact that the rectified current flows in the opposite direction to the true thermoelectric current produced by heating the junction.

The same is true of a carbon-steel and of a tellurium-aluminium junction, except for the last at low voltages.

It is clear also that we are here dealing with a contact phenomenon which depends on area of contact and pressure, for if these surfaces are sufficiently large and in good contact the rectification entirely disappears. The fact that the direct currents are roughly proportional to the square of the alternating currents suggests, however, a thermal origin for the effect. There seem to be a very large number of these combinations of non-metals and metals which possess this rectifying power on trains of oscillations.

Thus G. W. Pickard has found that a rough surface of a mass of fused zinc oxide or of native red oxide of zinc in contact with a brass point also rectifies oscillations, and may be used as a detector in association with a telephone as already described.[85] The name "Perikon" was applied by G. W. Pickard, in U.S.A. Patent Specification No. 886,154, to the contact rectifying detector made with fused oxide of zinc and a brass point, but it is now applied also to the rectifying contact detector consisting of chalcopyrite or copper pyrites in contact with zincite or native oxide of zinc, see U.S.A. Patent Specification No. 912,726.

The author has devised a convenient arrangement for using and testing contact cymoscopes or wave detectors depending upon the rectifying power of a contact of two substances. One of these bodies, M (see Fig. 36), is held in a grip, and the other in the form of a point, C, is pressed against it by a screw, S, with divided head; the whole being enclosed under a glass shade to exclude dust. Terminals T and T′ are connected respectively to the two substances in contact.

The property of rectifying alternating currents and electric oscillations in virtue of a unilateral conducting power for electricity is very marked in certain crystals. It was discovered in 1906 by General H. H. C. Dunwoody, of the United States army, that a mass of crystals of carborundum, which is an artificial silicide of carbon prepared in electric furnaces (see U.S.A. Patent of Acheson, No. 492,767 of 1893), can be used both with and without a local electromotive force as a detector of electric waves in

[84] W. L. Austin, *Bulletin of the Bureau of Standards*, Washington, U.S.A., vol. 5, No. 1, 1908.

[85] See G. W. Pickard, U.S.A. Patent Specifications, No. 886,154, also No. 912,613, of September 3, 1907, and No. 912,726.

radiotelegraphy.[86] If a single crystal of this substance is examined it will be found to have a hexagonal form and pale greenish colour, and to be somewhat translucent. The substance carborundum as usually obtained consists of a mass of such crystals arranged and compacted in an irregular manner. Each individual crystal is a rather poor conductor, but it possesses two marked characteristics, as shown by the measurements of G. W. Pickard[87] and G. W. Pierce.[88] In the first place, the crystal as a conductor possesses a unilateral conductivity, and in the next place, this conductivity does not obey Ohm's law, for the current-voltage curve is non-linear. Thus the curve in Fig. 37 shows the result of one set of observations by G. W. Pierce on the current in microamperes which passes through a crystal under certain applied voltages. Also, the curve in Fig. 37 shows the unilateral conductivity of the same specimen under direct and reversed electromotive force, as observed by Professor Pierce. This unilateral conductivity had been previously noted in the case of other minerals. Thus F. Braun, in 1874, found it in copper pyrites, iron pyrites, galena, and copper antimony sulphide, also in marked degree in psilomelan, a native oxide of manganese.

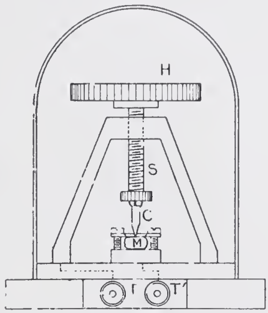


Fig. 36.—Contact Cymoscope. (Fleming.)

Braun could not find any evidence of electrolytic conduction or of thermoelectric effect in these cases to account for this curious asymmetry of conductance.

Professor Pierce has also discovered that the mineral hessite, which is as a telluride of silver or gold, and also anatase, which is an oxide of titanium, also possess similar properties, and will therefore rectify alternating currents.

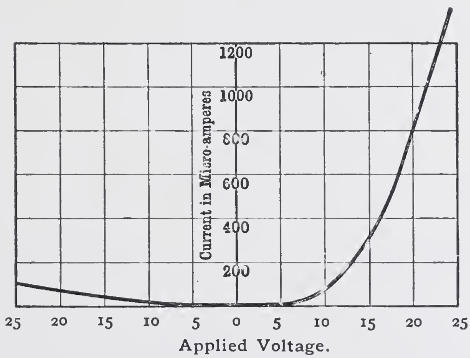


Fig. 37.—Characteristic Curves of Carborundum for + and − E.M.F.

In crystals of carborundum the unilateral conductivity is a function of the voltage applied, as shown by the figures in the Table below, which gives the current in microamperes in one direction and the reverse through a crystal tested by Professor Pierce with various voltages.

[86] See U.S.A. Patent Specification of H. H. C. Dunwoody, No. 837,616, of 1906; also British Patent Specification, No. 5332, of 1907.

[87] See G. W. Pickard, *Electrical World of New York*, vol. 48, p. 994, 1906.

[88] Also G. W. Pierce on "Crystal Rectifiers," *The Physical Review*, vol. 25, July, 1907.

Relation of Current to Voltage, showing Unilateral Conductivity of Carborundum.

Volts.	Current in microamperes.		
	C Commutator left.	C′ Commutator right.	$\frac{C}{C'}$
10·1	100	1	100
12·1	150	—	—
12·8	200	—	—
14·5	300	5	60
16·0	400	—	—
16·8	500	10	50
17·7	600	—	—
19·4	700	—	—
20·0	800	20	40
21·0	900	—	—
21·9	1000	30	33
23·2	1200	50	24
25·0	1500	—	—
27·5	2000	120	17

It will be seen that for this crystal under an impressed electromotive force of 10 volts the current in one direction is 100 times greater than in the opposite. Pierce found that in one specimen of carborundum, platinized on parts of its surface to make an improved contact, the current under an electromotive force of 34·5 volts was 527 times as great in one direction as in the opposite, and in another case under an electromotive force of 30 volts it was 3000 to 4000 as great. Up to the present no satisfactory explanation has been found of this curious fact.

Corresponding to these two properties of certain crystals, viz. the unilateral conductivity and the non-linear character of the current-voltage or conductivity curve, there are two methods by which they may be used as oscillation detectors in connection with radiotelegraphy. We may use them as Dunwoody first showed by placing the carborundum crystal in series with the oscillation circuit, whether antenna or coupled closed condenser circuit, and we may shunt the crystal by a telephone which has in series with it also a shunted voltaic cell so as to insert a fraction of a volt in the telephone circuit. There is, then, normally a certain current flowing through the crystal in one direction, and the voltage must be applied in the direction in which the crystal conducts best.

If, then, electric oscillations are superimposed on this unidirectional current by electric waves falling on the antenna, the steady E.M.F. acting on the crystal is periodically increased and decreased. Since, however, the current voltage curve is non-linear the mean value of this pulsating current may be greater than the current due to the steady E.M.F., and hence the addition of the oscillations causes an increase in the currents through the telephone and it therefore emits a sound. From the curve in Fig. 38, it will be seen that the current through a certain crystal corresponding to 2 volts steady E.M.F. is

4 microamperes. If, however, we add and subtract periodically 0·5 volt, then the currents due to 2·5 and 1·5 volts are respectively 8 and 2 microamperes, the mean of which is 5 microamperes. Hence the addition of the periodic E.M.F. of ± 0·5 increases the current through the crystal.

In the second place, we may, as Dunwoody also showed, dispense with the local cell and rely simply on the rectifying power of the crystal. In this case we simply shunt the crystal by a high resistance telephone, and if the crystal is placed either in the oscillation circuit or across the terminals of a condenser inserted in the circuit, a sound will be heard when intermittent oscillations fall on the crystal.

Another rectifying contact detector much employed in Germany consists of a plumbago point in light contact with a piece of galena or native sulphide of lead. Professor Pierce has shown that an excellent rectifying contact is obtained by pressing a copper point upon a crystal or flat piece of molybdenite, and that the rectification is not thermoelectric in nature.

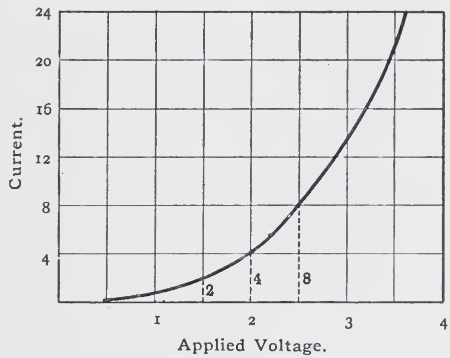


Fig. 38.—Characteristic Curve of Carborundum Crystal.

14. Electrodynamic Detectors.—Since high frequency alternating currents or electrical oscillations create magnetic fields varying in a similar manner round the conductor through which they pass, and since these fluctuating fields can induce other currents in closed metallic circuits, we may construct electric wave detectors which depend for their operation upon electrodynamic forces of attraction and repulsion.

One such form of detector has been employed in researches by Professor G. W. Pierce.[89] It is a form of alternating current ammeter devised in 1887 by the author.[90] The writer showed then that if a silver or copper disc is suspended by a fine wire within a circular coil, so placed that the plane of the disc makes an angle of 45° with the axis of the coil, when an alternating current flows through the coil it will induce secondary currents in the disc, and the electromagnetic repulsion between the primary and induced currents will cause the disc to move so that its plane lies more nearly at right angles to the plane of the coil [91] (see Fig. 17, Chap. II.). The theory of the instrument has already been given in Chap. II. § 13.

This copper-disc alternating current galvanometer was employed

[89] See G. W. Pierce, "Experiments on Resonance in Wireless Telegraphy Circuits," *The Physical Review*, September, 1904, vol. 19, p. 201.

[90] See *The Electrician*, May 6, 1887.

[91] For an explanation of this fact, the reader is referred to the author's treatise on the "Alternate Current Transformer," vol. i. 3rd ed. § 12, p. 307.

by the author to measure telephone currents and other feeble alternating currents in 1887. More recently Professor Pierce increased the delicacy of the instrument by employing a disc of silver paper suspended by a quartz fibre, the disc being hung at an angle of 45° inside an ebonite tube, on the outside of which was wound a coil of insulated wire. A small fragment of silvered glass attached to the disc served to reflect a ray of light upon a scale, and indicated any movement of the disc. With this instrument quantitative measurements can be made of electric oscillations taking place in a circuit. Very much the same device has been employed by Fessenden,[92] who used a suspended silver ring and two fixed coils on either side of it, through which the oscillations passed.

This form of cymoscope, like the thermal instruments, measures the root-mean-square or integral value of the oscillations. The mechanical forces, however, are small, and these electrodynamic instruments are not as sensitive as even the best forms of thermal detector.

15. Ionized Gas Oscillation Detectors.—The peculiar qualities of gaseous conductors, especially rarefied gases in so-called vacuum tubes, have been utilized for the detection and measurement of electric oscillations, and therefore of electric waves.

Professor Righi availed himself of one striking peculiarity of rarefied gases as conductors, as follows: It is well known, as first shown by Varley, that if a glass tube having platinum electrodes sealed into it, and a vacuum of about one-thousandth of an atmosphere made in it, is subjected to electromotive force, no current will flow through it until a certain voltage, say of 300 volts or so, is exceeded. Beyond that limit the current which flows is almost exactly proportional to the excess of the voltage above this critical value. Hence, if a small vacuum tube is connected in series with a battery of voltaic cells giving some voltage a little less than the critical value, no glow will take place in the vacuum tube, because no current passes. If, however, the same circuit includes a coil in which electric oscillations are excited, then the electromotive force of these induced oscillations will, in one direction, be added to the electromotive force of the battery, and will send a current through the gas and cause it to glow. Righi employed a vacuum tube in which a very small space intervened between the electrodes, and employed a water battery or some simple form of primary voltaic cell to produce the required "boosting" or auxiliary electromotive force.

The vacuum tube then glowed when electric oscillations were set up in the coil in series with it.

L. Zehnder employed a vacuum tube in a slightly different manner as a detector of Hertz oscillations.[93] He took advantage of another well-known fact connected with electrical discharge through rarefied gases.

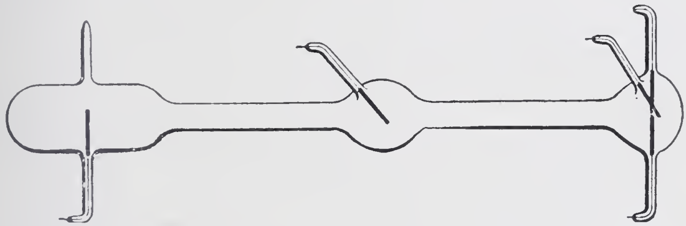
A vacuum tube of the ordinary kind has, in addition to the usual

[92] See U.S.A. Patent Specification, No. 706,735, application of December 15, 1899.

[93] See "The Objective Representation of Hertz's Researches in Electrical Radiation," by L. Zehnder, *Wied. Annalen der Physik*, 1892, vol. 47, p. 82; also *The Electrician*, 1892, vol. 30, p. 253.

platinum electrodes, another pair of electrodes at right angles, placed with their ends very close (see Fig. 39). If, then, a high potential battery, say of 300 or 400 cells, is applied in series with a high resistance, and the tube used in the ordinary way, we may adjust the number of cells until the electromotive force is just not sufficient to cause a glow discharge in the tube. Then if a very small discharge is sent between the transverse electrodes, this glow discharge causes the general mass of the rarefied gas to become a conductor for the steady battery electromotive force, and the vacuum tube bursts into glow. This arrangement is sometimes called a Zehnder "trigger tube," because the small transverse discharge, so to speak, sets off the longitudinal discharge in the tube. The transverse electrodes which convey the oscillatory discharge through the gas are placed quite close to the cathode of the continuous current electrodes, since it is known that at the cathode the great resistance to discharge is situated. In this manner a Hertzian spark too feeble to be visible at a distance can be rendered manifest by its power to start off another discharge from a powerful battery acting on the same mass of rarefied gas.

A third method of utilizing the properties of rarefied gases for the



From "The Electrician."

FIG. 39.—Zehnder's Trigger Vacuum Cymoscope.

purposes of a cymoscope was discovered by the author in 1904, based on a fact discovered by him in 1890 in the course of some investigations upon incandescent electrical lamps.[94]

If we seal into a glass bulb highly exhausted two-carbon filaments like incandescent lamps (see Fig. 40 *b*), we find that when both these filaments are cold, the vacuum or highly rarefied air left in the bulb is a very perfect non-conductor of electricity. Even an induction coil will not send a discharge through the bulb if the exhaustion has been pushed far enough.

If, however, the carbon filaments are made incandescent by insulated batteries, then it is found that the electromotive force of a single cell is sufficient to send a current across the interspace between the filaments. It is, necessary, however, to connect the galvanometer and single cell between the two ends of the carbon filaments, which are in connection with the negative poles of the respective insulated batteries. We may employ a single carbon filament and a metal plate or cylinder surrounding it (see Fig. 40 *a*, or 40 *c*), and if we then render

[94] See J. A. Fleming, "On Electric Discharge between Electrodes at Different Temperatures in Air and High Vacua," *Proc. Roy. Soc. Lond.*, 1890, vol. 47, p. 122; also *Proc. Roy. Institution*, vol. 13, p. 45, Friday Evening Discourse, Feb. 14, 1890.

the carbon filament incandescent by a local battery, it is found that a single cell will pass a current through the vacuous space between the cylinder and the hot filament, provided that this single cell has its negative pole in connection with that end of the filament which is itself in connection with the negative end of the heating battery. If the connections of the single cell are reversed, then no current passes.

The space between the cold cylinder and the hot carbon filaments possesses, therefore, a unilateral conductivity. Negative electricity can pass from the hot filament to the cold metal cylinder through the highly rarefied gas, but not in the opposite direction. The arrangement acts as an *electrical valve* for electric currents. The author furthermore discovered that this device could be used to separate out the two constituent currents of an electrical oscillation,[95] and so render it possible for an electrical oscillation to affect an ordinary galvanometer or a train of oscillations affect a telephone.

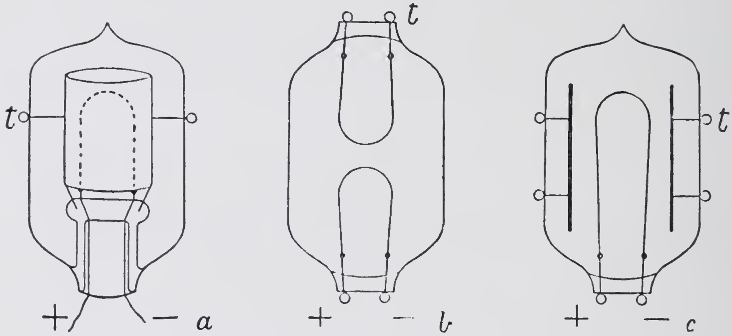


Fig. 40.—Fleming Oscillation Valves.

To do this the valve, now called an oscillation valve, is used as follows :—

One of the above-described bulbs, O, has a sensitive galvanometer, G, placed in series with the secondary coil *s* of an oscillation transformer joined in between its metal cylinder and the negative terminal of the carbon filament (see Fig. 41). If electric oscillations are induced in this secondary circuit by a primary coil, *p*, then when the carbon filament is made incandescent by an insulated battery, B, only one of the currents forming the oscillation is allowed to pass, viz. that in which the movement of negative electricity is from the carbon filament to the metal cylinder through the vacuous space. The galvanometer, therefore, is affected only by the flow of electricity in one direction, and its needle or coil is therefore deflected. In each train of oscillation the positive currents are, so to speak, sifted out from the negative, and only one set allowed to pass. We are therefore able to employ a sensitive mirror galvanometer of the ordinary type to detect the existence of electric oscillations in a circuit.

When the rectifying quality of the valve is to be used for

[95] See J. A. Fleming, "On the Conversion of Electric Oscillations into Continuous Currents by means of a Vacuum Valve," *Proc. Roy. Soc. Lond.*, 1905, vol. 74, p. 476.

detecting electric waves, or as a receiver in wireless telegraphy, the oscillation transformer, P, S, associated with the antenna A has its primary circuit included between the aerial wire, A, and the earth, E (see Fig. 42).

The secondary circuit of the transformer is closed by a condenser, C, and to one terminal of this condenser is connected the cylinder or plate of the valve O, and to the other the negative terminal of the filament. A local battery, B, is employed to incandesce this filament. A telephone T is inserted in the circuit.

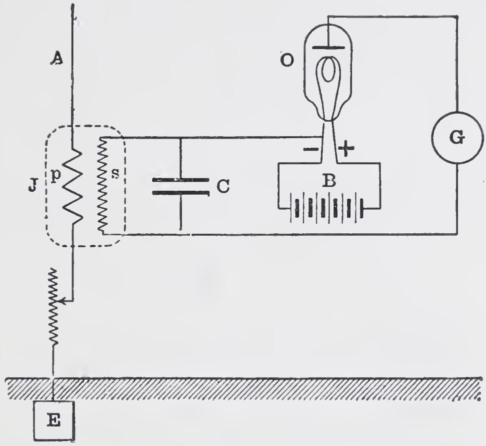


FIG. 41.—Vacuum Valve used to rectify Electric Oscillations and render them detectable by an Ordinary Galvanometer, G.

When electric waves fall on the antenna they excite oscillations in the condenser C, and these are rectified by the unilateral conductivity of the rarefied gas between the filament and the cylinder, and so affect the telephone.[96]

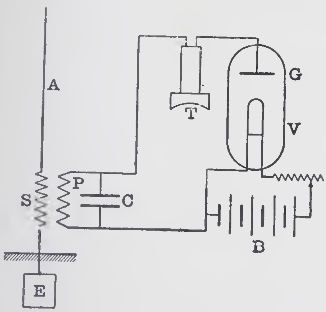


FIG. 42. — Fleming Oscillation Valve used as a Cymoscope or Electric Wave Detector in Wireless Telegraphy. A, antenna; V, valve; B, heating battery; T, telephone; E, earth plate.

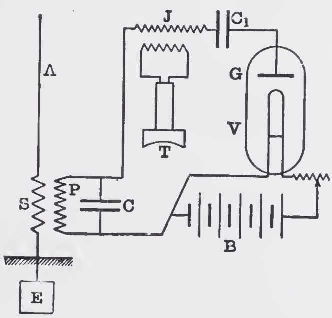


FIG. 43.—Marconi's Arrangement of Circuits for using the Fleming Oscillation Valve as a Radiotelegraphic Receiver.

Mr. Marconi modified this arrangement of the author's in 1907 by inserting an additional transformer, J, and condenser, C_1, as shown in Fig. 43.[97]

[96] See British Patent Specification, No. 24,850, November 16, of 1904, J. A. Fleming; also U.S.A. Patent Specification, No. 803,684, of April 19, 1905; and German Patent, No. 186,034, issued May 6, 1907.

[97] See British Patent Specification, No. 887, of 1907, G. Marconi.

In both Mr. Marconi's and the author's above-described methods of employing the valve, we are utilizing the unilateral conductivity of the ionized gas which it possesses in virtue of the electrons discharged from the incandescent filament.

On the other hand, we may employ this detector in another manner, depending on the fact that such ionized gas does not obey Ohm's law as a conductor.

It is well known that the conductivity of rarefied gases differs in quality from that of metals or electrolytes. If we apply a steadily increasing electromotive force to a mass of rarefied gas by means of two electrodes, the negative one being incandescent, then the current through the gas does not increase proportionately to the electromotive force. The current rises up to a maximum value, at which it is said

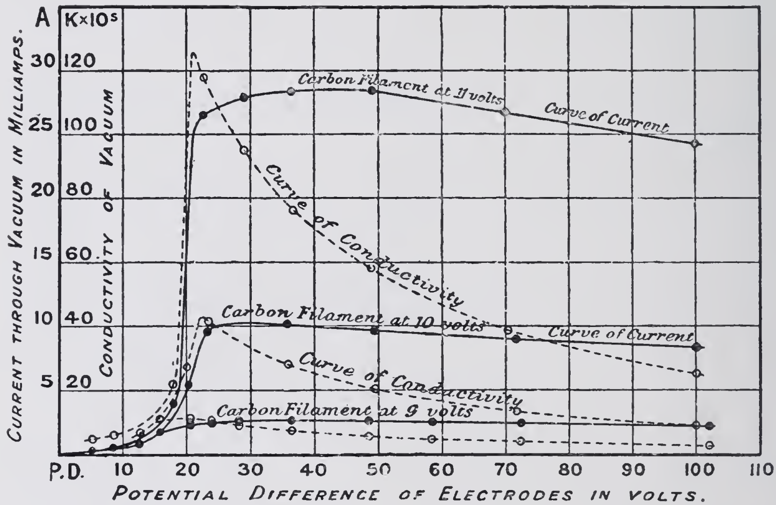


FIG. 44.—Curve showing the Variation of Current through an Oscillation Valve with Increasing Potential Difference between the Negative Carbon Filament Terminal and Insulated Plate.

to be saturated.[98] Hence the gas, as a conductor, does not obey Ohm's law. Also the conductivity, which is the ratio of current to voltage, rises to a maximum and then falls off. The curves in Fig. 44 show how the current and conductivity of the vacuous space vary in one of the above-described oscillation valves when increasing voltages are applied between the metal cylinder and the carbon filament, the latter heated to various temperatures.

The resistance of the vacuous space may therefore vary from millions of ohms to a few ohms, according to the voltage applied and the temperature of the filament. The valve rectifies the oscillations or becomes more completely unilateral in conductivity the colder the metal cylinder is kept. If we allow the cylinder to become warmed by radiation from the filament, then the flow of electricity between

[98] See *Proc. Roy. Soc. Lond.*, 1905, vol. 74, p. 483; also Prof. Sir J. J. Thomson, on "Conduction of Electricity through Gases," chap. viii.

the carbon filament and cylinder is not altogether in one direction. When made as shown in Fig. 40, and used with a carbon filament at that temperature at which it is working at about 3 watts per candle, the rectification is from 80 to 85 per cent.

If we consider a portion of the characteristic or current-voltage curve which lies between the origin and the knee of the curve (which is shown on an enlarged scale in Fig. 45), we shall find that its curvature is not constant, and corresponding to certain abscissæ representing a steady voltage applied to the ionized gas there is a current of a certain value. If, however, we increase and diminish the voltage by small amounts, as by superposing an alternating voltage on the steady voltage, then the corresponding currents have a mean value which will be greater than the current corresponding to the steady voltage, as already explained in connection with the carborundum crystal (see Fig. 38).

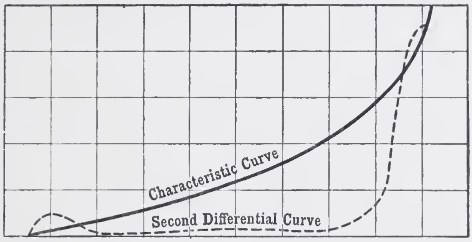


FIG. 45.—Lower part of the Characteristic Curve of Highly Rarefied Gas between Heated Electrodes.

Hence if we apply this critical steady voltage in series with the ionized gas and with a telephone, we shall find that the addition in the circuit of an alternating voltage creates a sound in the telephone.

Accordingly, we can make use of this property of the ionized gas, viz. that its current-voltage curve is not linear, in other words, that it does not obey Ohm's law, in the following manner: An oscillation circuit (see Fig. 46), consisting of a condenser and one coil of an oscillation transformer, is coupled to an antenna which is in series with the other coil of the oscillation transformer. To one terminal of the condenser in the oscillation circuit is attached the cylinder of the vacuum valve. The filament of the valve is rendered incandescent by a local battery, B, and regulated by a variable rheostat in series with it. This battery is also shunted by a high resistance, r, having a sliding contact upon it, and this contact is connected with the other terminal of the condenser in the oscillation circuit through a telephone. It will be seen, therefore, that this arrangement is equivalent to putting a certain exactly adjustable steady voltage in series with the telephone and the ionized gas of the valve, and also making arrangements for

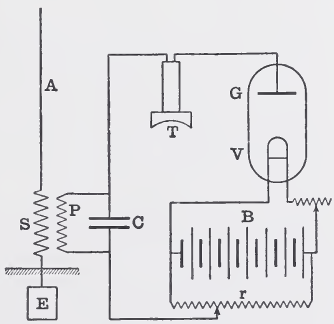


FIG. 46.—Diagram of Circuits when using the Fleming Oscillation Valve as a Cymoscope based on the Non-linear form of the Characteristic Curve of Rarefied Gas.

superimposing upon this critical steady voltage an oscillatory voltage derived from oscillations set up in the condenser circuit. If, then, the slider on the rheostat, r, is adjusted to a position such that the voltage applied to the ionized gas is exactly sufficient to bring it to that point on the characteristic curve at which a sudden change of curvature takes place, or change in conductivity, then it will be seen that the setting-up oscillations in the condenser circuit will superpose upon this steady voltage an alternating voltage, and in accordance with the principles just above explained, this will cause a greater current to flow through the telephone, and a sound will therefore be produced in the telephone if electric waves continue to fall upon the antenna. The author has since found that greatly improved results can be obtained by employing a particular type of glow lamp with a tungsten filament and an insulated cylinder of copper surrounding it. The electronic emission from the tungsten is greater than from carbon, probably because it is a better conductor, and can be raised without volatilization to a much higher temperature than carbon.[99] The author now uses this tungsten glow lamp detector as above described. It will therefore be seen that both with the crystal and ionized gas detectors there are two methods of procedure in using them as radiotelegraphic receivers. We may either make use of the property of unilateral conductivity possessed by these substances and rectify trains of oscillations by means of them, or we may make use of the non-linear character of the characteristic curve. H. Brandes has already pointed out that all detectors, or combinations of detectors which do not follow Ohm's law, are capable of acting as detectors for electric oscillations owing to their rectifying effect. It would be more correct to say that they can be used as detectors of electric oscillations in virtue of the fact that their characteristic curves exhibit changes of curvature at certain points, and that therefore the superposition of an alternating voltage upon a steady voltage may be caused to create an increase of current through such a conductor.

As a radiotelegraphic oscillation detector precisely similar or else closely resembling the author's oscillation valve above described has been denominated by Mr. Lee de Forest an *audion*, and claimed by him as a novel invention of his own, it may be well in the interests of scientific history to recapitulate the facts on which the author relies in support of his own priority of invention. As far back as 1889 the author had independently noted (see *Proc. Roy. Soc. Lond.*, vol. 47, p. 118, 1890) the unilateral conductivity of rarefied gases when one of the electrodes (the cathode) was rendered incandescent. In 1896 the author described experiments on the Edison effect in glow lamps (see *Phil. Mag.*, July, 1896), in which this fact was further illustrated. In November, 1904, the author discovered that a glow lamp with a metal plate sealed into the bulb carried on a third insulated terminal sealed through the glass, might be used to rectify electric oscillations. This appliance was patented in Great Britain by the author on November 16, 1904 (No. 24,850 of 1904) as a radiotelegraphic detector. In the early part of 1905, such glow lamps were made as oscillation detectors for wireless telegraphy for the author and so used by Mr. Marconi. This oscillation valve was also described in a paper read on February 9, 1905, to the Royal Society of London and also in one read to the Physical Society of London, March 23, 1906. This was also patented as a radiotelegraphic receiver in the United States, applied for April 19, 1905, and granted as No. 803,684, dated November 7, 1905. It was

[99] See British Patent Specification of J. A. Fleming, No. 13,518, of 1908.

also patented in Germany as from April 12, 1905, the patent (No. 186,084) being issued on May 6, 1907.

It is therefore abundantly clear that before October, 1906, a glow lamp having a metal plate sealed into the bulb was described, used, and patented by the author as a radiotelegraphic receiver. Yet at this date, October, 1906, Mr. Lee de Forest described identically the same device as an invention of his own under the name of an *audion* in a paper read before the American Institute of Electrical Engineers. Since that date he has employed a modification of it in which a metal plate and a grid are enclosed in the bulb in place of a single plate. The metal plate is connected by a circuit outside the bulb with the negative terminal of the incandescent filament, a telephone and a battery being inserted in this circuit. The metal grid is connected by a circuit outside the bulb with one terminal of a condenser in the receiving circuit, the other terminal of this condenser being connected with the positive terminal of the incandescent filament.

Although the scheme of circuits is somewhat different from that used by the author or by Mr. Marconi, yet the operation of the glow lamp with metal plates inserted in its bulb is essentially that of a rectifier of trains of oscillations depending on the fact of the unilateral conductivity of rarefied gases when one electrode of the gaseous conductor part of the circuit is incandescent and the other cold. The audion is not therefore essentially a different invention from the author's oscillation valve, no matter how used (see editorial remarks, *Jahrbuch der Drahtlose Telegraphie*, vol. i. p. 595, 1908, "Drahtlose Telephonie nach de Forest")

16. General Considerations concerning Electric Wave-detecting Devices.—From the descriptions that have been given in the previous sections of various forms of wave-detecting device or cymoscope, it will be apparent that they may be divided into two broad classes: (1) those that depend essentially upon the action of electromotive force or electric force—these are commonly called potential-actuated devices; (2) those that depend essentially for their action upon the operation of electric current—these are commonly called current-operated devices.

Then, furthermore, we may divide them in another way: (1) into those devices the action of which is dependent upon the maximum value of the current or electromotive forces during a train of electrical oscillations—this generally means that the device is actuated by the amplitude of the first oscillation, whether we are considering potential or current; (2) those devices the operation of which depends, not upon the maximum value, but upon the integral or root-mean-square value of either the current or the potential during one complete train or a number of trains; otherwise we may say that in this last case the wave detector measures, not the amplitude of the first or any particular oscillation, but the root-mean-square value of the whole of the oscillations.

As particular instances of these, it may be noted that coherers or contact cymoscopes of all kinds are generally called potential-operated devices, and are for the most part influenced by the maximum value of the oscillations, that is, by the amplitude of the largest oscillation. This is not strictly always the case, because the high initial resistance of the coherer or imperfect contact may be broken down by the repeated application of a high frequency alternating potential, so that even if the change of resistance does not take place under the action of the first oscillation it will take place if the oscillations continue to act. The ordinary metallic filings coherer acts in this manner. It possesses initial high resistance which may amount to several thousand ohms, and it possesses a certain small but definite electrostatic capacity. In fact, we may view the ordinary metallic filings coherer

in its initial condition as if it consisted of a number of small spheres immersed in a dielectric. Such a system of conductors would have a certain definite capacity, and when acted upon by electric force exceeding a certain limit the dielectric between the spheres would be pierced and discharge would take place, resulting in an immediate drop to a much lower resistance and to almost complete metallic continuity or conductivity through the mass. As we shall see in a later chapter in discussing syntonic telegraphy, there are some objections attending the employment of a cymoscope which suddenly alters its resistance or capacity in the act of being influenced.

In the next place, we may take the magnetic detector as a good illustration of a current-operated cymoscope or wave detector. In this case the effective agent is the actual current which passes, and, moreover, it is the maximum value of that current or of the first oscillation, which is the chief factor in producing the demagnetization of the iron or the annulment of the hysteresis which occurs. The magnetic detector, however, differs from the coherer essentially in the fact that there is no change in resistance or capacity in the circuit through which the oscillations flow when the change produced by them takes place; hence, as we shall see, the magnetic detector is more adapted as receiver in a certain type of electric wave telegraphy. It may then be noted that all forms of thermal wave detector or cymoscope are dependent for their action, not upon the maximum value of the oscillations, but upon the root-mean-square value. This establishes a very important difference between thermal cymoscopes on the one hand and the magnetic cymoscopes on the other, for since the root-mean-square value of the current during a unit of time depends upon the number of groups of oscillations which take place, it follows that the indications of a thermal cymoscope are not merely dependent upon the maximum value of the oscillations during one train, or the rate at which the oscillations decay, but upon the number of groups of oscillations which occur per second. Hence any irregularity in the occurrence in the groups of oscillations is a disturbing cause, and the thermal cymoscope or bolometer cannot be employed for metrical purposes unless great precautions are taken to control the uniformity of the spark discharges of the transmitter.

As regards vacuum-tube cymoscopes. In some cases these depend for their action upon the maximum value of the oscillations during a train, as in Zehnder's vacuum tube; whereas in other cases, as in the author's oscillation valve, the indication of the galvanometer associated with it is dependent upon the mean value of the oscillations during a unit of time, and therefore upon the frequency of the groups of oscillations.

In discussing the application of these various forms of cymoscope in wireless telegraphy, in a later chapter, we shall have occasion to notice some further peculiarities and the special adaptability of certain forms of cymoscope to certain classes of telegraphic work.

17. Wave Measuring Instruments or Cymometers.—In addition to detecting the existence of electric waves passing through space by the oscillations which they can create in a linear conductor incident upon it, we often desire to measure the wave length of these waves,

either those sent out from a radiator or those received by a detector. In those cases in which the radiation is taking place, from a rod or wire in which high frequency oscillations are set up, the wave length λ of the radiation is connected with the frequency n of the oscillations in the linear oscillator by the formula $V = n\lambda$, where $V = 3 \times 10^{10}$ cms. per second or is the velocity of radiation. Hence to determine the wave length it suffices to determine the frequency of the oscillations in the radiator. Suppose that the radiator is inductively associated with another closed circuit, and the radiator is a Marconi aerial wire. There are several methods by which we can ascertain the frequency of the oscillations taking place in this aerial wire. The following instruments have been invented for this purpose, and those devised by the author have been called by him *cymometers*. One form of instrument depends upon the establishment of stationary waves upon an associated helix.

We have already explained, in Chap. IV., the conditions under which stationary electric oscillations of potential and current can be established upon an insulated helix of wire. Suppose that we have a helix consisting of a long ebonite rod, say 2 ms. long and 5 cms. in diameter, wound over uniformly with a long spiral of fine silk-covered copper wire. This wire may suitably be of the size known as No. 32 S.W.G., and on such an ebonite core it will be possible then to wind in one layer of closely adjacent turns a helix of 5000 turns. Let such a helix, K_1K_2, be supported on insulating stands (see Fig. 47) a couple of feet above a table in contiguity to an antenna, A, in which it is desired to measure the frequency. To some point near to the base of the aerial is attached a small insulated metal plate, which acts as one plate of a small air condenser, C_1, the other plate being connected to one end of the above-described insulated helix. On this helix slides a curved metal saddle, D, which is packed with tinfoil to make it fit the helix closely, and this saddle is connected by a wire with an earth plate, E_2. We provide also a Neon, or other vacuum tube, V. Let us assume, then, that the oscillations are excited in the aerial wire; we can move the saddle along the helix until such a position is found that one complete stationary wave of potential on the helix is included between the saddle and the end attached to the small air condenser. When this is the case, if we explore the space round the helix between these points with a Neon vacuum tube, we shall find that just over the end of the saddle the Neon tube does not glow, also it does not glow at a point halfway between the saddle and the condenser end, also it does not glow just at the end next the condenser. In order that this may be the case, it is necessary to shield the helix from indirect action of the oscillation in the aerial or the spark of the transmitter; it is necessary to place a metal plate (not shown in the diagram) close to the end of the helix which is in connection with the aerial. This plate must be perforated by a hole large enough to allow the end of the helix just to pass through, the air gap being large enough to prevent sparking from the end of the helix to this plate. This guard plate must also be connected to the earth by a wire. By moving the saddle about, it is then possible to find a position in which there is a node of potential over the saddle near the earth plate, and also halfway between, whilst at

intermediate positions, $\frac{1}{4}$ of the way and $\frac{3}{4}$ of the way, there is an antinode and loop of potential, as indicated by a dotted line in the diagram in Fig. 47.

We have already explained, in Chap. IV., that the velocity with which the potential wave moves along the helix is inversely proportional to the square root of the capacity and inductance per unit of length of the helix, and we have shown how these quantities can be accurately measured. Hence this velocity can be determined for

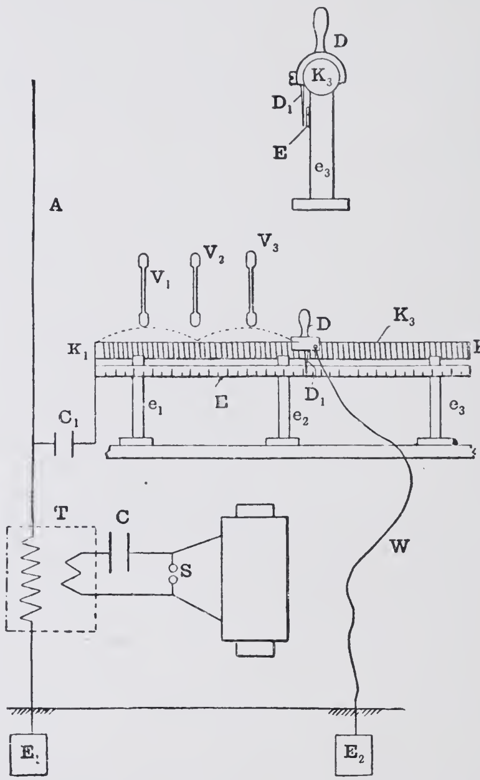


Fig. 47.—Helix Cymometer. (Fleming.) K_1, K_2, helix of wire; D, sliding saddle; C, coupling condenser; A, antenna.

the helix in use in centimetres per second. By means of a scale, E, we can also measure the observed wave length on the helix as indicated by the distance of the saddle from the earth plate, when the potential distribution is as above described. The quotient of this velocity along the helix by the observed wave length gives us the frequency of the stationary oscillations on the helix. This must also be the frequency of the oscillations in the aerial wire. Hence, if v stands for the velocity of propagation of the oscillations along the helix, and λ for the wave length on the helix, or the length K_1D, then, if Λ stands for the wave length of the waves sent out into space

from the aerial, we have the following formula for this wave length:—

$$\Lambda = \lambda \frac{3 \times 10^{10}}{v}$$

In the above formula v must be measured in centimetres per second, and λ and Λ in the same linear units.

In this manner, given a helix sufficiently long, we can determine the frequency of the oscillations in any aerial wire, and therefore the wave length of the waves sent out into space from it.

The author has also devised a form of direct-reading portable cymometer, by which not only can the wave lengths of waves used in wireless telegraphy be immediately ascertained, but also by its aid numerous measurements, such as the measurement of small capacities, inductances, and coefficients of coupling of oscillation transformers, can be made with great ease.[100] This instrument is constructed as follows:—

It consists of a condenser of variable capacity constructed of a tube of brass covered with ebonite, on the outside of which another concentric tube fits closely, but not so tightly as to prevent easy movement. If the tubes lie over one another, such a double brass tube with interposed tube of ebonite constitutes a tubular condenser, but if the outer tube is more or less slid off the inner brass tube the capacity is reduced almost proportionately to the displacement of the outer tube. Again, if we have a wire wound in the form of a helix round an ebonite tube, the turns being close together but not touching, and if we have some form of clip which can be slid along the helix so as to make use of more or less of the spiral, we have a variable inductance.

These two appliances are combined together in the cymometer in such a way as to form a complete oscillatory circuit; the inner end of the tubular condenser (see Fig. 49) is connected to one end of the helix of wire by a copper bar, and the outer condenser tube is connected to the helix by an embracing clip, so that as the outer condenser tube is displaced from the inner tube to reduce the capacity, the effective inductance in the circuit due to the spiral is reduced in the same proportion. The helix and the tubular condenser, which may be formed of two or more tubes, are mounted on a board, and by means of a handle the condenser tube can be moved and the inductance and capacity simultaneously altered, and in the same proportion. The arrangement of the instrument is as shown in Fig. 48, and the scheme of connection as in Fig. 49. If, then, we place the long copper bar connecting the helix and condenser near but not very close to any other circuit in which oscillations are taking place, we can tune the cymometer circuit to the other circuit by moving the handle so as to vary the inductance and capacity of the cymometer. We must also have some means of determining when the current in the cymometer, or the potential difference of the tubes forming the condenser, is a maximum.

[100] See J. A. Fleming, "The Application of the Cymometer to the Determination of the Coefficient of Coupling of Oscillation Transformers," *Phil. Mag.*, 1905, ser. 6, vol. 9, p. 758; also *Proc. Phys. Soc. Lond.*, 1905, vol. xix. p. 603.

The author discovered that the most convenient way of doing this was by the use of a vacuum tube of the spectrum type, filled with Neon. Neon is a rare gas contained in the atmosphere, about

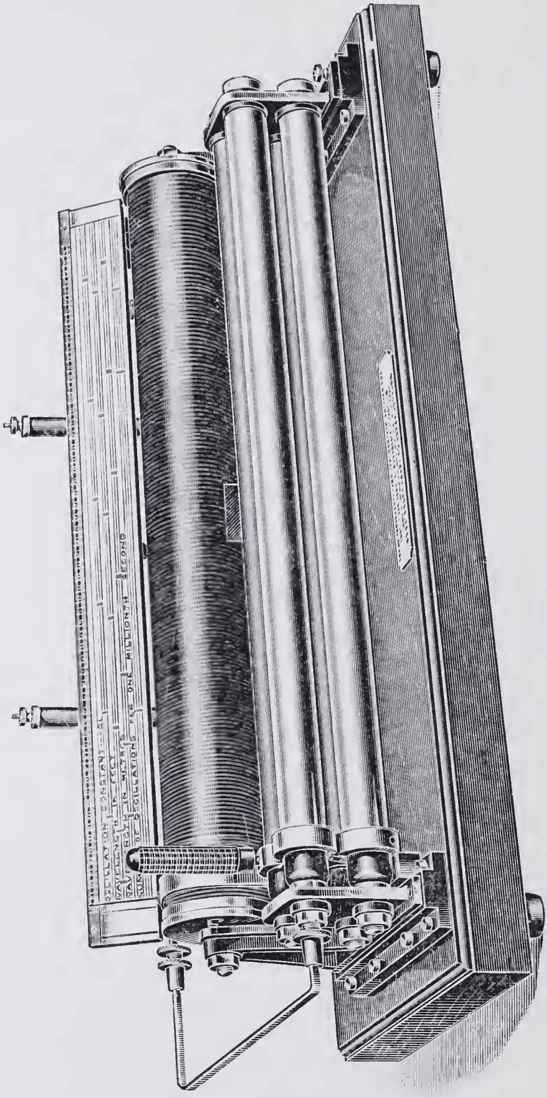


Fig. 48.—The Fleming Cymometer.

80,000th part by volume, and it is remarkable for its small dielectric strength and for the great brilliancy of the glow produced in it when placed in an alternating current field. If such a Neon tube is connected to the terminals of the tubular condenser, then, when the

capacity and inductance are altered and the oscillation in the cymometer circuit thereby increased up to a maximum, it is easy to determine the position when this maximum takes place by the Neon tube beginning to glow, or glowing most brilliantly. The most recent

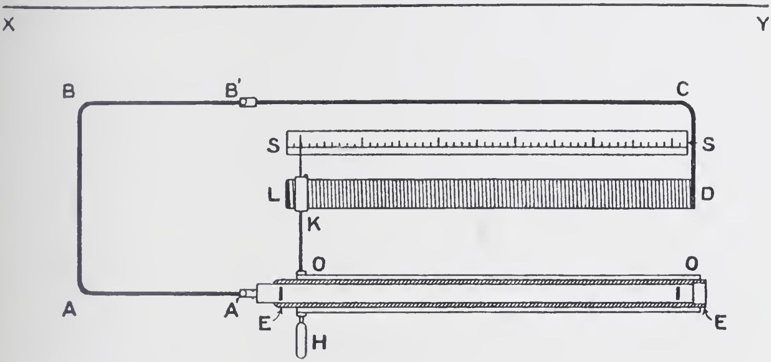


Fig. 49.

form of the cymometer is shown in Fig. 50, in which a screw motion is provided for varying the capacity and inductance very slowly.

Another method of discovering when the current is a maximum

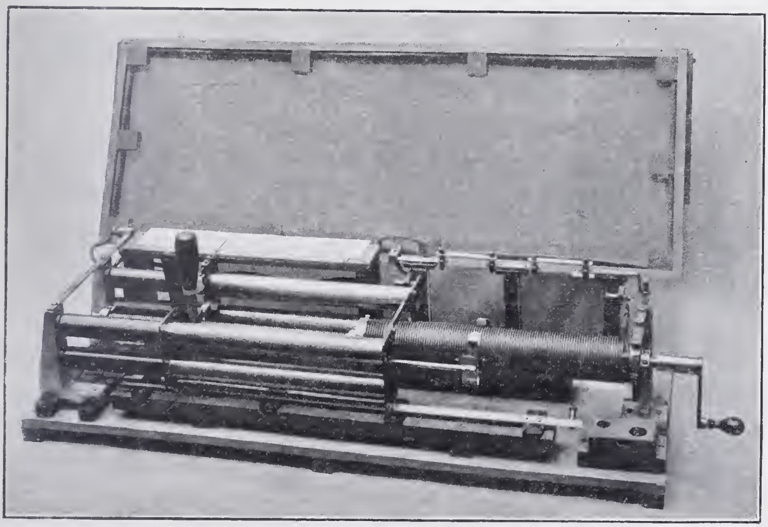


Fig. 50.—Recent Type of Fleming Cymometer for Measuring the Wave Lengths of Radiotelegraphic Waves.

in the cymometer circuit is by inserting in the circuit of the copper connecting bar a fine wire of high resistance about a centimetre in length, having in contact with it a very sensitive thermo-junction of bismuth and iron. This thermo-junction is connected to a sensitive

galvanometer, preferably a Paul single-pivot, low-resistance galvanometer (see Fig. 51). If then by the movement of the handle of the cymometer it is gradually tuned with any adjacent circuit in which oscillations are taking place, the increase in the current up to a maximum will be indicated by a gradual increasing deflection of the galvanometer, and it is quite easy to determine that adjustment of the cymometer in which the current is a maximum.

The cymometer has a graduated scale with a pointer moving over it, and the instrument is calibrated by the manufacturer so as to show at a glance the frequency corresponding to any particular adjustment of the tubular condenser. The author has designed such instruments for reading frequencies from 50,000 up to 5,000,000, and the appearance of the complete instrument is as shown in Figs. 48 and 51.

From the above descriptions it is evident that cymometers or wavemeters may be divided into the two broad classes of *open* and *closed* circuit instruments.

The general principles which must guide us in the construction

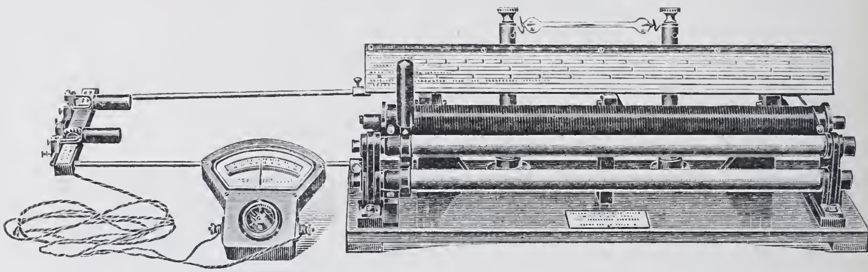


Fig. 51.

or selection of a wavemeter have been well stated by Professor A. Slaby.[101]

In the first place, it is obvious that the measuring instrument must not disturb the natural frequency of the oscillation it is desired to measure. If we wish to measure the pressure of gas in a vessel or the electrical potential difference between two points, it is clear that our pressure gauge or voltmeter must not alter the value of the quantity we desire to measure by the very act of connecting the instrument used to take a measurement. If it does, although we may obtain a reading, we do not obtain the real value of the quantity we are seeking.

In the same way, if we wish to know the frequency of the oscillations in any circuit, then it is clear that the instrument we employ must not alter the capacity or inductance of the circuit tested in the act of making a measurement. As the capacities and inductances with which we are concerned are generally very small, it is quite easy to be misled on this matter. Hence, if we are testing the frequency of the oscillations in an aerial wire, as used in wireless telegraphy, it is of the utmost importance not to disturb the small capacity of

[101] See *Elektrotechnische Zeitschrift*, December 10, 1903, vol. 24, p. 1007.

the aerial by connecting to it any object which will sensibly increase it. Also we must not increase its inductance by making loops or curves in it.

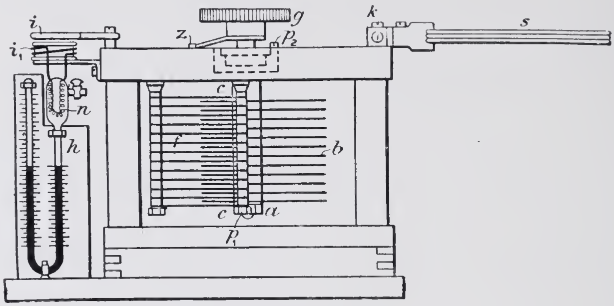
In all forms of open circuit or helix cymometer there is a great loss of energy by radiation. Hence these generally require more applied energy to work them than do the best forms of closed-circuit cymometer.

We may also distinguish cymometers by the mode in which they are coupled to the circuit, open or closed, in which the oscillations exist, the frequency of which we desire to know. This coupling may be electrostatic or electromagnetic, and involve either a capacity or a mutual inductance. In either case this coupling capacity or mutual inductance must be very small, for the reasons already given. It is easier to render the mutual inductance small, and better, therefore, to employ a closed-circuit cymometer. Hence the author has given preference to the closed-circuit form in the instrument designed by him.

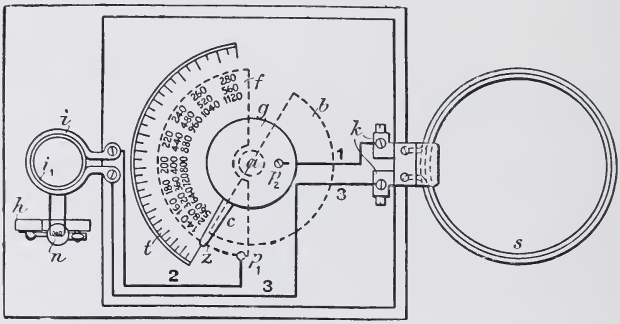
Another form of closed-circuit wavemeter has been designed by J. Dönitz.[102] He employs an arrangement consisting of a circular coil having a definite inductance, in series with a condenser made of series of semicircular discs, the capacity of which can be varied within limits by the revolution of these discs on an axis, the arrangement of the condenser plates somewhat resembling that of a Kelvin multicellular voltmeter (see Figs. 52 and 53). These plates are immersed in insulating oil. In inductive connection with part of the circuit is another small circuit, including a fine-wire platinum coil sealed up in the bulb of an air-thermometer. Hence the production of the maximum current in the inductance coil and condenser is estimated by the reading of the air-thermometer becoming a maximum. The instrument is used as follows: If it is desired to measure the frequency, and therefore the wave length, of the oscillations in any circuit open or closed, a loop is formed on that circuit, which is placed parallel to and at some little distance from the circular coil of the wavemeter. The oscillations in the first circuit are then permitted to induce others in the wavemeter circuit, and the capacity of this last is altered by varying the condenser until the air-thermometer gives its maximum reading. When this is the case, it is assumed that the time period of the two oscillations is the same, that of the wavemeter being, of course, known from the known inductance and capacity of the circuit. Various coils are provided with the instrument to give it a suitable range of measuring power. Other forms of cymometer, consisting of a straight helix of wire, have been devised by Professor Slaby, and also by G. Seibt and von Arco.

The principle on which these instruments work is that if a helix of uninsulated wire is held in the hand, and the other end held near to a circuit, such as an aerial wire in which electric oscillations of potential are taking place, then we can alter the length of the helix until it is such that stationary oscillations are excited in it of the same frequency as those in the circuit tested. The helix will have its

[102] See *Elektrotechnische Zeitschrift*, 1903, vol. 24, pp. 920–925, No. 5; also *The Electrician*, January 1, 1904, vol. 52, p. 407; also German Patent, No. 149,350, Class 21 G.



(*Elevation.*)



(*Plan.*)

FIG. 52.—Dönitz Wavemeter.

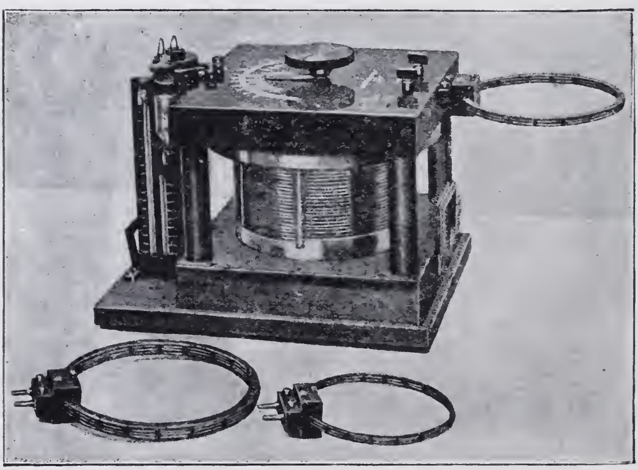


FIG. 53.—Dönitz Wavemeter. (*Perspective view.*)

fundamental oscillation when its length is nearly one quarter of the wave length on it corresponding to that frequency, as explained in Chap. IV.

Professor Slaby's solution of the problem is to provide a series of solenoids of wire of various lengths, wound on glass tubes, the turns being insulated slightly from each other. These solenoids are capable of being effectively shortened by a sliding contact. A solenoid is held in the hand by one end, and the other end presented to the aerial. The solenoid has its effective length then varied until the maximum glow appears at its outer end. This is detected by the fluorescence produced on a barium platinocyanide screen, through which particles of gold leaf are distributed, and then it is assumed that the solenoid has had an oscillation set up in it corresponding to its fundamental oscillation, and having a wave length therefore equal to four times the length of the solenoid wire. The end of the solenoid must not be brought nearer to the aerial than 1 or 2 feet (see Fig. 54).

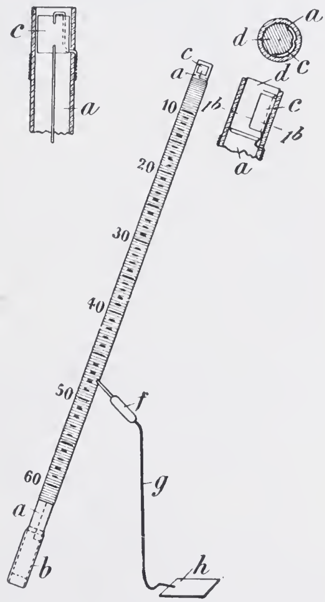


Fig. 54.—Slaby's Helix Wavemeter. *ab*, graduated wire helix; *h*, earth plate; *f*, sliding contact.

It appears that very similar arrangements employing an open or straight resonance coil had previously been employed by Dr. G. Seibt (*Elektrotechnische Zeitschrift*, 1903, No. 1; or *The Electrician*, vol. 50, p. 777).

In the use, however, of a straight resonance coil for this purpose, great care is necessary to ascertain that the oscillation set up in the resonance solenoid is the fundamental, and not a higher harmonic.

The diagram in Fig. 54, taken from a Patent Specification by Professor Slaby, shows the details of this helix wavemeter. A thin insulated copper wire is wound in a close spiral on a glass tube of 0·75 inch diameter. The lower end of the copper wire is in conductive connection with a metal handle attached to the glass tube. The upper end of the copper wire is connected with the fluorescent sheet. This is formed of a small sheet of paper covered with crystals of barium platinocyanide, gold leaf in a fine state of division being then rubbed on the surface. The sheet of paper so prepared is inserted in the upper end of the glass tube, and kept in by a stopper.

Also a blunt metal point or rod is provided, which is connected by a wire with the earth. To use the instrument, the end of the spiral at which the fluorescent paper is placed is presented to the circuit in which the oscillations are taking place, and the blunt metal earthed rod is moved along the spiral until the brightest glow is produced in the fluorescent paper by the electric brush discharge, which takes

place against it from the outer or free end of the helix. A scale can be marked on the helix, showing at once the wave length or the frequency in the oscillating circuit being tested.

18. Measurements made with the Cymometer—Frequency and Wave Length.—The following measurements can then be made with the cymometer or equivalent forms of wavemeter.

1. *Frequency.*—It has already been shown that the frequency of the oscillations in a circuit having a capacity of C microfarads and the inductance L microhenrys, is given by the formula—

$$n = \frac{10^6}{2\pi\sqrt{C_{\text{mfds.}} \, L_{\text{mhys.}}}}$$

or if the inductance is measured in absolute electromagnetic units or centimetres, then the frequency is given by the formula—

$$n = \frac{5{\cdot}033 \times 10^6}{\sqrt{C_{\text{mfds.}} \, L_{\text{cms.}}}}$$

If, then, we desire to determine the frequency of the oscillations in an antenna or other circuit, we place the bar of the cymometer in contiguity to that circuit, and move the handle of the cymometer along slowly until the cymometer circuit is in resonance with the other. This will be indicated by the Neon tube bursting into glow, or the galvanometer needle (if the thermoelectric couple is used) taking its maximum deflection. If the cymometer is direct reading, we can then see at once the frequency, or if the instrumental reading gives us the oscillation constant (O) of the circuit, viz. the product of the capacity of the circuit in microfarads ($C_{\text{mfds.}}$) and the inductance in centimetres ($L_{\text{cms.}}$), then the frequency is obtained from the formula—

$$n = \frac{5{\cdot}033 \times 10^6}{\sqrt{C_{\text{mfds.}} \times L_{\text{cms.}}}} = \frac{5{\cdot}033 \times 10^6}{O}$$

2. *Wave Length.*—In all cases of wave motion there is a relation between the velocity of the wave, V, its frequency, n, and wave length, λ, expressed by the equation—

$$V = n\lambda$$

The velocity of the electromagnetic waves being 300 million metres per second, or very nearly one thousand million feet per second, it follows that the wave length is at once obtained by dividing this last number by the frequency. Hence, if the frequency of the oscillations in an antenna is determined, we have the wave length of the emitted waves. If, then, we can determine the oscillation constant of the antenna, or of the circuit which is radiating, we have at once the following rules:—

Wave length in feet = 195·56 × oscillation constant.

Wave length in metres = 59·6 × oscillation constant.

Frequency in millionths of a second is 5·033 ÷ oscillation constant.

In order to determine the wave length, therefore, all that is necessary is to place the bar of the cymometer parallel, but not

very near to a portion of the lower part of the antenna. For this purpose, a yard or two of the antenna may be laid in a horizontal position, if necessary. On exciting the oscillations in the antenna and moving the handle of the cymometer, we shall find a position in which the Neon tube glows most brilliantly if the cymometer has a suitable range. In the case of inductively coupled antennæ, it will be found, of course, that there are two wave lengths being emitted, and therefore two positions in which the Neon tube has a maximum glow. In so using the cymometer, it is desirable to put the bar as far as possible from the antenna after having roughly discovered the approximate wave length, and then to take a fresh reading, so adjusting the distance of the cymometer bar from the antenna, that the Neon tube only just glows on passing through to a position of resonance. With a little care it is possible to determine the wave lengths of the order of 1000 or 1500 feet within 10 feet.

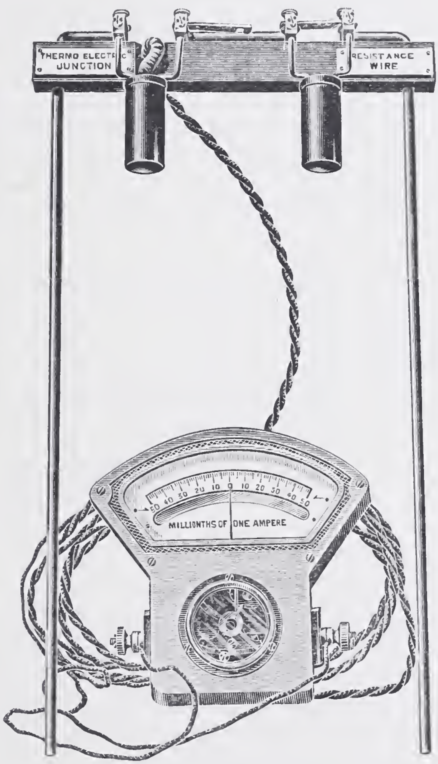


FIG. 55.

Four types of cymometers are now made, one suitable for measuring from about 30 metres to 1000 metres, another up to 1500 metres, a third up to 2000 metres, and a fourth up to 3000 metres, the lowest possible reading being generally about one-twelfth part of the highest possible reading for any one instrument, but with special cases greater ranges can be obtained. Hence a suitable cymometer must be employed for the particular measurements being made, the oscillation constants of the above four types ranging from about 1 to 12, 2 to 25, 3 to 37, and 4 to 50. For measurements in which greater accuracy of reading is required, it is better to employ, instead of the Neon tube, the thermoelectric detector, which is placed in the circuit of the cymometer. The circuit of the cymometer is cut in two places, or the simple double copper bend with which it is usually provided for completing the circuit can be replaced by a special double bend (see Fig. 55) containing two cuts in it, in one of which is inserted a fine resistance wire, and in the other a fine resistance wire having a thermoelectric junction in contact with it. These resistances and

thermoelectric junction are contained in two ebonite boxes attached to the special bend, and a length of flexible connecting wire is provided, by which the thermoelectric junction is connected to a special low-resistance, single-pivot sensitive galvanometer, that usually employed being made by Paul. There are short-circuiting straps for cutting out the thermoelectric junction resistance, or the plain resistance. If we insert in the circuit only the resistance with the thermojunction, and then employ the cymometer as above described, in proximity to any circuit in which oscillations are taking place, we shall find that as the handle is moved, tuning the cymometer more and more in circuit with the circuit under test, the ammeter exhibits a gradually increasing deflection, and at a certain position of the cymometer a maximum deflection is reached. In this position, therefore, the cymometer circuit is traversed by the maximum current, and, therefore, is in resonance with the circuit under test.

19. Measurement of Small Capacities and Inductances by the Cymometer.—The cymometer may be employed for the measurement of small capacities and inductances in the following manner:—

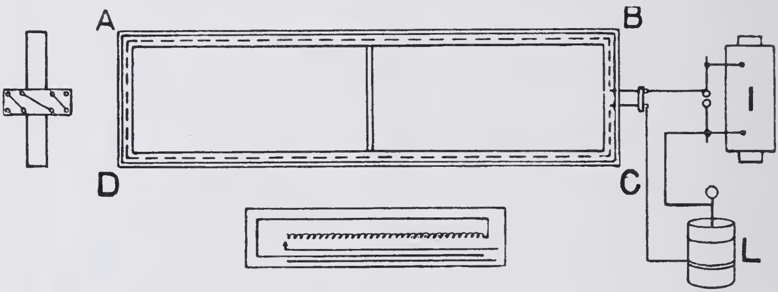


FIG. 56.

Each instrument is, or can be, supplied with a standard inductance consisting of one or more turns of insulated wire arranged round a rectangular frame. These inductances vary from about 4000 cms., or four microhenrys, up to 75,000 cms., or 75 microhenrys, depending on the pattern of cymometer in use. If, then, a certain small capacity, say, that of a Leyden jar, has to be determined, it is done in the following manner. The jar is placed upon a sheet of ebonite, and one coating is connected to one secondary spark ball of an induction coil, the other coating or terminal of the condenser being connected to one end of the above-mentioned standard inductance, whilst a second end of the standard inductance is connected to the other secondary spark ball (see Fig. 56). The spark gap, condenser, and inductance are all connected in series. The cymometer is then placed with its copper bar parallel, not very near to one side of the standard inductance. On working the coil, oscillations are set up in the circuit of the jar and inductance, and the handle of the cymometer is moved until the Neon tube glows most brightly. The scale reading of the cymometer then shows the oscillation constant of the cymometer in that position, that is to say,

the value of the square root of the product of its capacity in microfarads, and its inductance in centimetres in its then position. The value of this quantity is called the *oscillation constant*, and is marked on the scale. It then follows that the oscillation constant for the circuit containing the unknown capacity must be the same. Hence, if we square the value of the oscillation constant and divide by the value of the standard inductance in centimetres, we have the value of the unknown capacity in microfarads. Thus, for example, suppose that the standard inductance is 5000 cms., and that the maximum glow in the Neon tube occurs when the cymometer pointer indicates an oscillation constant 10 on the scale, then the square of 10 being 100, and the quotient of $100 \div 5000$ being $\frac{1}{50}$, we know that the capacity of the condenser in question must be $\frac{1}{50}$ of a microfarad. The rule therefore is as follows: Square the oscillation constant and divide by the value of the standard inductance in centimetres, and the resulting quotient is the capacity of the jar or condenser in fractions of a microfarad.

In the same way the cymometer can be used with a standard condenser to determine the value of an unknown inductance, for if we determine as above described the capacity of a condenser by the aid of the cymometer, then join up this capacity with the unknown inductance and the spark gap, to form an oscillation circuit, putting in, if necessary, a yard of straight wire to lie parallel with the bar of the cymometer, and if we then determine the oscillation constant of this circuit, and find it to be O, then the inductance in the circuit must be equal to $\frac{O^2}{C}$, where C is the capacity of the condenser in microfarads, and this quotient gives the inductance in centimetres.

In those cases where a small inductance is measured, it can be determined as the difference between two inductances, viz. by joining up with the condenser of known capacity a standard inductance of known value, determining the oscillation constant as above, and then increasing the inductance of that oscillation circuit by adding in the small unknown inductance, and making a redetermination of the oscillation constant. Supposing, for instance, that the oscillation constant in the first instance is O_1, and in the second O_2, and that the standard inductance was, say, 5000 cms., and the value of the unknown and small inductance L, then we have the following equations:—

$$\frac{O_1^2}{C} = 5000$$

$$\frac{O_2^2}{C} = 5000 + L$$

$$L = \frac{O_2^2 - O_1^2}{C}$$

from which we can at once determine the value of L.

A large variety of such tests can be made with a cymometer, provided it is remembered that the oscillation constant marked on the scale of the cymometer is the square root of the product of its capacity reckoned in microfarads and its inductance in centimetres,

corresponding to the position in which the handle of the cymometer is then placed.

The calculated value of the inductance L of a rectangular-shaped circuit made of round-sectioned copper wire may be obtained by the formula already given.[103]

The expression for L is as follows :—

$$L = 4\left\{(S + S')\log_\epsilon \frac{4SS'}{d} - S\log_\epsilon (S + \sqrt{S^2 + S'^2}) \right.$$
$$\left. - S'\log_\epsilon (S' + \sqrt{S^2 + S'^2}) + 2\sqrt{S^2 + S'^2} - 2(S + S')\right\} \quad (1)$$

where S and S′ are the lengths of the two sides of the rectangle, and d is the diameter of the round copper wire of which it is made.

The above formula is a strictly accurate one for infinite frequency, and can easily be applied to any case of a real rectangular circuit. The logarithms are, of course, Napierian.

We can therefore construct a rectangular circuit of wire attached to the lid of the box of the cymometer, which has a known predetermined inductance of, say, 5000 cms. Strictly speaking, there is a small correction for the tails of parallel wire which connect the rectangle to the jar at one end and to the coil at the other. If considered necessary, this may be taken into account by employing a reduced case of the above formula for the inductance of the rectangle.

If there be a pair of circular-sectioned wires of diameter d placed at a distance D apart, the inductance for a length l of the parallel wires is given by the formula

$$L' = 4l\left(\log_\epsilon \frac{2D}{d}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Hence, if the length of the tails of wire at each end of the rectangle is the same, and equal to l, the inductance of the whole circuit is equal to $L_1 + 2L'$, where L_1 and L' have the values given by the formulæ above.

We can always check the result by using as a loop some form of circuit of which the inductance can be calculated.

Thus, if we bend a bare round-sectioned copper wire into a square, with the ends brought quite near together, we can predetermine its inductance.

We have here a reduced case of the general formula for a rectangular circuit. In expression above put $S = S'$, and put $4S = l$, then the formula reduces to—

$$L = 2l\left(\log \frac{4l}{d} - 2{\cdot}853\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Strictly speaking, we should add to the value of the expressions (1) and (3) for the inductance of a rectangle and a square a term equal to $\frac{R'}{2\pi n}$, where R′ is the high frequency resistance corresponding to a frequency n. The formulæ (1) and (3), as they stand, give the inductance for infinite frequency. The value of $\frac{R'}{2\pi n}$ is, however,

[103] See Chap. II. p. 134.

generally negligible compared with the other term, and the expressions given may be taken to be the inductances for any frequency of the order of 10^6.

In the next place, we may employ the same instrument to determine the coefficient of coupling of the circuits of an air core transformer, such as an oscillation transformer used in wireless telegraphy. Suppose the inductance of the primary circuit to be denoted by L, that of the secondary by N, and the mutual inductance by M. Then $\frac{M}{\sqrt{LN}}$ is called the *coefficient of coupling*, and is a quantity of importance in the theory of high frequency transformers.

We may join the two circuits of the oscillation transformer into one circuit, so that they assist or oppose each other in creating co-linked flux. In one case the effective inductance is equal to $L + 2M + N$, and in the other case it is $L - 2M + N$.

Hence if we treat the oscillation transformer, so joined up in the two ways, and measure as above its effective inductances, and call them L_1 and L_2, we have—

$$L_1 = L + 2M + N$$
$$L_2 = L - 2M + N$$
$$\text{Hence} \quad M = \frac{L_1 - L_2}{4}$$
$$\text{and} \quad L + N = \frac{L_1 + L_2}{2}$$

We can then determine directly and independently the larger of the two inductances L or N, and hence we can calculate the value of $\frac{M}{\sqrt{LN}}$, or the coefficient of coupling of the circuits. As an instance of such a determination, we may give the measurements made with a form of oscillation transformer used in wireless telegraphy. The primary circuit consisted of one single turn composed of eight turns of 7/22 insulated copper wire in parallel wound round a square wooden frame. The secondary circuit consisted of nine turns of the same standard wire wound over the primary circuit. The resultant inductances were measured by the cymometer with the circuits joined up to add and oppose each other.

The measured values were as follows:—

$$L_1 = L + 2M + N = 62{,}576 \text{ cms.}$$
$$L_2 = L - 2M + N = 49{,}621 \quad ,,$$
$$N = 55{,}445 \quad ,,$$
$$\text{whence we have} \quad M = 3239 \quad ,,$$
$$\text{and} \quad L + N = 56{,}098 \quad ,,$$
$$\text{therefore } L = 653 \quad ,,$$
$$\text{and } N = 55{,}445 \quad ,,$$
$$\text{therefore} \quad \frac{M}{\sqrt{LN}} = 0{\cdot}54 \quad ,,$$

The coupling would therefore be called "close," as it is usual to call the coupling "close" or "tight" when the coefficient exceeds 0·5, and "loose" when it is smaller. The theory of the above-described instrument is involved in that of oscillation transformers generally, which has already been discussed.[104]

If there be two circuits each having inductance and capacity adjusted so that when separate and far apart each has the same oscillation constant and the same natural frequency n_0, then when these circuits are coupled together inductively with a coefficient of coupling $k = \frac{M}{\sqrt{L_1 L_2}}$, where M is the mutual inductance and L_1 and L_2 the inductances of each circuit separately, it has been shown that we have created in the secondary circuit not one but two oscillations of different frequencies, n_1 and n_2, such that—

$$\left.\begin{aligned} n_1 &= n_0 \frac{1}{\sqrt{1-k}} \\ n_2 &= n_0 \frac{1}{\sqrt{1+k}} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The condition that n_1 and n_2 should be equal, and equal to n_0, is that $k = 0$. If the coefficient of coupling is not small, that is, if the mutual inductance of the two circuits is not small, we cannot employ a resonant or adjustable secondary circuit to ascertain the natural frequency of the oscillations in a primary circuit when the secondary circuit is not present. If the adjustable secondary circuit is the circuit as described of a cymometer, then in order that its indications may be correct there must be a very small mutual inductance between the cymometer circuit and the circuit we are testing.

It is evident, therefore, that if a circuit has in it oscillations of a certain frequency n_0, and we couple it inductively with another circuit which can be adjusted to have the same oscillation constant $\sqrt{CL}$, in order that oscillations of only one single frequency equal to n_0 should be induced in this adjustable circuit, it is essential that the coefficient of coupling k of the two circuits should be very small. Otherwise two oscillations of different frequency are excited, the frequency of one being greater and that of the other less than that of the free independent original frequency n_0 it is desired to determine.

In the form of cymometer here described, this necessary condition is fulfilled by making the mutual inductance between the cymometer and the circuit being tested very small. We have then to employ a sensitive detector for the condition of resonance, viz. a Neon vacuum tube. One characteristic of the author's form of cymometer is that only a small portion of the whole inductance of the cymometer takes part in creating mutual inductance. Another is that one single movement of a handle varies simultaneously and in the same proportion both the capacity and inductance of the instrument. In using a cymometer for measuring the frequency of the oscillations in any circuit, we have to be on our guard against disturbing the very quantity we wish to measure, or setting up in the cymometer circuit some

[104] See Chap. III. p. 260, § 11.

oscillation of a different frequency. It is an obvious deduction from the above investigation, that in using the cymometer we should place the bar of the cymometer as far away as possible from the circuits being tested. We can make use of the cymometer itself to demonstrate the fact that in the close coupling of isochronous circuits we have oscillations of two periodicities set up. Thus suppose we have two circuits of the same time-period when separated and we couple them together inductively. Then, if we investigate with the cymometer the oscillations set up in the secondary circuit, we find it to be a complex oscillation resolvable into components of different periods. The cymometer therefore acts just like an electrical spectroscope. It resolves the complex vibrations in a circuit into their simple components and shows us what they are. This effect is very marked in the case of inductively coupled aerials in wireless telegraphy. If we have a nearly closed condenser circuit with spark gap in which oscillations are set up, which is inductively coupled to an aerial or antenna, then, even if the two circuits are, in common language, "tuned" to each other, so that they have the same independent time period, yet when coupled, if coupled at all tightly, there are two oscillations set up in the aerial of different frequencies, and two waves radiated of different wave length, which may differ in length by 15 or 20 per cent.

20. The Measurement of the Logarithmic Decrement of Oscillations by the Cymometer.—The cymometer, or other direct reading wavemeter, affords also a ready means of obtaining the decrement of the oscillations in any circuit.

For this purpose it is employed to delineate a resonance curve, and from this curve the sum of the decrements of the cymometer and of the circuit under test can be obtained as explained in Chap. III. § 14. For this purpose we must provide the cymometer circuit with a hot-wire ammeter to read the mean-square value of the oscillations set up in its circuit. In the author's cymometer the current in the oscillatory circuit of the instrument is measured by inserting in it a short length of very fine wire against which is soldered a thermojunction consisting of a fine bismuth and fine iron wire. The high resistance wire consists of a length of about 3–5 cms. of constantan wire 0·05 mm. in diameter, having a resistance of about 6 or 7 ohms. If oscillations are passed through the constantan wire it is heated, and an E.M.F. is created in the thermojunction. This last is connected to a low-resistance single pivot Paul galvanometer as already described, so that this instrument is deflected by an amount depending on the mean-square value of the oscillations heating the thermojunction. If we pass through the fine wire various measured continuous currents, and note the steady deflection of the galvanometer, we know that any oscillations, damped or undamped, which subsequently produce the same deflection of the galvanometer, must be producing heat at the same rate, and therefore must have the same mean-square value as the direct current. In addition to this thermojunction wire, which serves the purpose of a hot-wire ammeter for small currents, we provide also another similar wire, but without a thermojunction, which can be inserted in the cymometer circuit at pleasure.

Let us suppose, then, that it is desired to examine the oscillations

in any condenser circuit-produced damped oscillations. A part of this last circuit must be brought near to a part of the testing or cymometer circuit so that it acts inductively on it but feebly. The cymometer circuit must then have its capacity and inductance, or both, varied slowly and at each setting; the natural frequency, n, of its circuit must be known, and also the root-mean-square value, a, of the current induced in its circuit. If there is only one single oscillation in the circuit under test having a frequency, N, then when the cymometer circuit is set to have this frequency the current in it will have a maximum value, A. If we insert in the cymometer circuit the known small resistance, R, then this will increase its damping by a known amount and the maximum current will be reduced to A′. If we call δ_1 the decrement of the primary circuit, δ_2 that of the cymometer, and δ_2' that due to the added resistance, R, then we have—

$$\delta_2' = \frac{R}{4N_1L_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where N and L_2 are the natural frequency and inductance of the cymometer corresponding to the position of resonance. Then by the formulæ already given (see Chap. III., § 14) we have—

$$\delta_1 + \delta_2 = \pi\left(1 - \frac{n}{N}\right)\sqrt{\frac{a^2}{A^2 - a^2}} \quad . \quad . \quad . \quad . \quad (6)$$

The observations are plotted as follows:—

Having observed the values of a and n over a sufficient range, we plot a curve having abscissæ $\frac{n}{N}$ and ordinates $\frac{a}{A}$, and the result is a resonance curve for the case in question, as shown in Fig. 57.

Since the frequency is connected with the oscillation constant by the formula $n = \frac{5\cdot033 \times 10^6}{O}$, we can also write the above formula of Drude and Bjerknes in the following form:—

$$\delta_1 + \delta_2 = 3\cdot1416\,\frac{O_2 - O_1}{O_2}\sqrt{\frac{a^2}{A^2 - a^2}} \quad . \quad . \quad . \quad . \quad (7)$$

In plotting out the resonance curve as above described, it is best to take the mean-square value of the maximum curve as unity, and to correct the other currents in the corresponding ratio; and the same way for the frequencies, viz. the resonance frequency and any other frequency. If, then, we put x for $\left(1 - \frac{n}{N}\right)$ and y for $\frac{a}{A}$, we can write the above formula for the sum of the decrements finally in the form—

$$\delta_1 + \delta_2 = 3\cdot1416\, x \frac{y}{\sqrt{1 - y^2}} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Since the resonance curve is not quite symmetrical with respect to its maximum ordinate, it is best to determine from the resonance curve the values of the frequency n lying on either side of the maximum

current, which correspond to any given value of the cymometer current, and to take the mean of these values as the value to be put into the above formula.

It will be seen, then, that from such a resonance curve we can determine the sum of the decrements of the circuits under test, and that of the cymometer. This last has, however, been increased by the resistance of the fine wire inserted in its circuit, by means of which we determine the sum of the decrements. We have therefore to eliminate the latter quantity as follows: Suppose we insert in the cymometer circuit the small resistance, R, and that we again take a

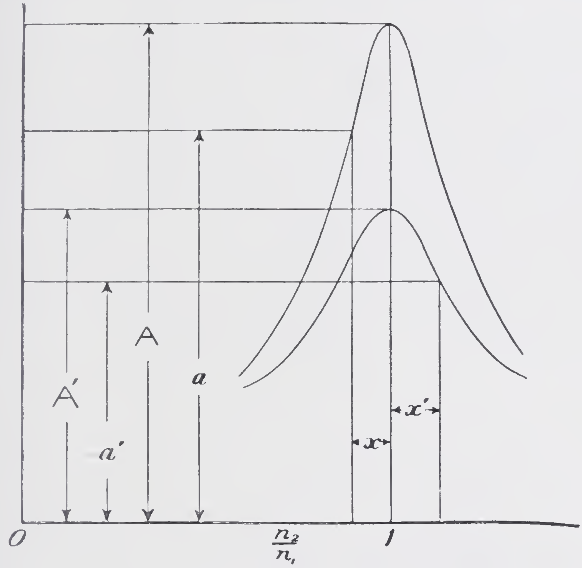


FIG. 57.—A Resonance Curve.

resonance curve. The decrement of the cymometer has been increased from δ_2 to $\delta_2 + \delta_2'$ where $\delta_2' = \frac{R}{4n_1 L_2}$, L_2 being the inductance of the cymometer circuit corresponding to the resonance frequency n_1. Now it has been shown in Chap. III. § 14, equation 166, that the mean-square value of the resonance current is inversely as the quantity $\delta_1\delta_2(\delta_1 + \delta_2)$. It follows therefore that if δ_2 is changed to $\delta_2 + \delta_2'$, and A^2 to A'^2, we must have the following relation, viz.—

$$A^2\delta_2(\delta_1 + \delta_2) = A'^2(\delta_2 + \delta_2')(\delta_1 + \delta_2 + \delta_2') \quad . \quad . \quad . \quad (9)$$

or if we put X for $\delta_1 + \delta_2$ and X′ for $\delta_1 + \delta_2 + \delta_2'$, we may write it in the form—

$$\delta_2 = \frac{X'\delta_2'}{\left(\frac{A}{A'}\right)^2 X - X'} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

But $$X = \delta + \delta_2$$

therefore
$$\delta_1 = X - \frac{X'\delta_2'}{\left(\frac{A}{A'}\right)^2 X - X'}$$

where
$$X = 3{\cdot}1416\, x \frac{y}{\sqrt{1 - y^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

To determine δ_1 we have therefore to take two resonance curves, one as above described, and another in which the circuit of the cymometer has its decrement increased by a known amount, by the insertion of a second fine wire resistance in the gap provided for it.

The details of the measurements will perhaps best be understood by going through the calculations in a particular case.

A certain oscillation circuit was set up, and by means of the cymometer a pair of resonance curves drawn, one without and one with an added small resistance in the cymometer circuit. These curves were as shown in Fig. 57. From these curves measurements were made giving us the R.M.S. values of the currents a, A, a', A', and at the same time of the quantities $x = 1 - \frac{n_2}{n_1}$ and $y = \frac{a}{A}$. A number of values of y were taken off the curve corresponding to various values of x not exceeding 0·05, and tabulated as under, and the value of $\delta_1 + \delta_2$ calculated by the formula above given.

$\frac{a}{A} = y$	$\left(1 - \frac{n_2}{n_1}\right) = x$	$X = \delta_1 + \delta_2$
0·95	0·0120	0·115
0·90	0·0165	0·112
0·85	0·0205	0·104
0·80	0·0255	0·107
0·75	0·0293	0·105
0·70	0·0335	0·103

The mean value of X is then 0·108.

In the same manner, after increasing the resistance of the cymometer circuit, a second set of values was obtained as follows :—

$\frac{a'}{A} = y$	$\left(1 - \frac{n_2}{n_1}\right) = x$	$X' = \delta_1 + \delta_2 + \delta_2'$
0·95	0·0125	0·120
0·90	0·0210	0·138
0·85	0·0255	0·130
0·80	0·0300	0·125
0·75	0·0345	0·124
0·70	0·0385	0·119

Hence the mean value of X' is 0·126.

Accordingly we have from the curves and formulæ above given

$$\left(\frac{A}{A'}\right) = 2{\cdot}34$$

$$\delta_1 + \delta_2 = 0{\cdot}108$$

$$\delta_1 + \delta_2 + \delta_2' = 0{\cdot}126$$

Hence

$$\delta_2' = 0{\cdot}018$$

$$\delta_2 = 0{\cdot}017$$

$$\delta_1 = 0{\cdot}091$$

The greater part of the decrement δ_2 is due to the resistance of fine wire thermo-junction, and apart from this the decrement of the cymometer in itself is only 0·005. In this case the oscillation circuit being tested comprised a condenser or Leyden jar and an inductance of 5000 cms. and a spark gap of 2 or 3 mm. in length. The high frequency resistance of the inductance was calculated from the dimensions of the wire and found to be 0·23 ohm. As this circuit was a nearly closed circuit, the decrement was all due to resistance, partly of the metallic wire R and partly of the spark r, and this can be shown to be equal to $4n_1L\delta_1$, where L is the inductance of the circuit, and n_1 the frequency corresponding to resonance. Hence, if R and r are measured in ohms and L in centimetres, we have

$$R + r = \frac{4n_1L\delta_1}{10^9}$$

But $R = 0{\cdot}23$, $L = 5000$, $\delta_1 = 0{\cdot}091$, and $n_1 = 0{\cdot}95 \times 10^6$. Hence $r = 1{\cdot}23$ ohms.

Also from the formula $M = \dfrac{4{\cdot}605 + \delta_1}{\delta_1}$ we can show that each train of oscillations comprised about 50 semi-oscillations, or 25 periods.

Accordingly, the measurement of the decrement gives us all information about the nature of the oscillations taking place and the resistance of the spark.

If we had been testing the decrement of a radiotelegraphic antenna, we should have found a much larger decrement than 0·091, because then there would have been radiation to increase the damping, and therefore the decrement.

It will be seen, therefore, that by the use of the cymometer and the necessary adjuncts to it, we are enabled to obtain all the required information concerning the oscillations in the antenna of a radiotelegraphic transmitter employing the spark method of producing damped oscillations. When operating as above upon an antenna which is inductively coupled to the condenser circuit, the resonance curves will be found to be curves with double humps, as in Fig. 33, Chap. III.; and if these humps are not too close to one another, we may apply the above process to each hump separately, and obtain the decrement of each of the two co-existing oscillations in the antenna.

In making these measurements, the cymometer must of course stand on a table, and a certain length of the antenna must be bent round so as to be parallel with, but not too near, the bar of the

cymometer. It will also be found necessary that the outer tube of the condenser should be connected to the earth by means of a terminal provided for that purpose.

We can make use of the measurements of decrement also to determine the high frequency resistance of any circuit. Thus, for instance, in the case of a particular primary circuit having an inductance of 5012 cms., and a capacity of 0·002645 mfd., and a spark gap of 1 mm., the resistance, R, added to the cymometer was 7·1 ohms, and the inductance L of the cymometer in that setting of the instrument corresponding to resonance was L = 5500 cms., and whilst the corresponding frequency = n = N was $1·25 \times 10^6$.

$$\text{Hence} \qquad \delta_2^1 = \frac{R}{4NL} = \frac{7·1 \times 10^9}{4 \times 1·25 \times 10^6 \times 5500} = 0·025$$

Also it was found that the resonance current A was 0·1195 amp. and that when the resistance of 7·1 ohms was inserted the resonance current A_1 was 0·0635 amp.

The observed corresponding values of $\frac{a}{A}$ and $\frac{n}{N}$ were then as recorded in the following Table.

OBSERVATIONS FOR THE DELINEATION OF A RESONANCE CURVE.

Cymometer current as percentage of maximum current $= 100 \frac{a}{A}$	Calculated value of $\pi\sqrt{\frac{a^2}{A^2 - a^2}}$	Measured value of $1 - \frac{n}{N}$	Calculated value of $\delta_1 + \delta_2$
95	9·58	0·0067	0·0643
90	6·47	0·0098	0·0635
85	5·09	0·0126	0·0642
80	4·18	0·0152	0·0636
75	3·58	0·0177	0·0635
70	3·08	0·0205	0·0632

The mean value of $\delta_1 + \delta_2 = 0·0637$

Hence from the other observed quantities we have, by equation (9)—

$$A^2 \times 0·0637 \times \delta_2 = A_1^2 \times (0·0637 + 0·0258) \times (\delta_2 + 0·0258)$$

Therefore, inserting the above given values of A and A_1, we have $\delta_2 = 0·017$, and therefore $\delta_1 = 0·0467$.

The high frequency resistance R_1 of the primary circuit must therefore be such that $\delta_1 = \frac{R_1}{4NL_1}$, where $N = 1·25 \times 10^6$ and $L_1 = 5012$ cms. Hence—

$$R_1 = 4 \times 1·25 \times 10^6 \times 5012 \times 0·0467 \times 10^{-9} \text{ ohms, or } 1·17 \text{ ohms,}$$

and since the high frequency resistance of the inductance itself was found to be 0·31 for that frequency, we find $1·17 - 0·31 = 0·86$ ohm as the resistance of the spark.

In taking these resonance curves it is a very great assistance to allow a steady blast of air under a pressure of about 16–20 inches of water to impinge on the gap between the spark balls. It not only keeps the balls cool, but blows away the arc which tends to form at each discharge, which would otherwise keep down the condenser terminal voltage.

21. Measurement of the Wave Length and Decrement of Incident Waves.—It is quite easy in the above-described manner to measure the wave length and damping of the waves sent out from a transmitting antenna. It is rather more difficult when we are concerned with the waves arriving on an antenna, since the oscillations set up in it are then much more feeble. The same principles, however, apply. It is merely a question of a more sensitive oscillation detecting instrument wherewith to measure the mean-square value of the oscillations in the receiving antenna.

The author has found that the most convenient detector for this purpose is the molybdenite-copper point rectifier of Professor G. W. Pierce. A small mass of molybdenite is held in a clip, and a copper point adjusted in light contact therewith. The contact has very effective unilateral conductivity, and rectifies the trains of oscillations so that they affect a high resistance telephone (1000 ohms) placed as a shunt across the condenser terminals of the cymometer.

The wave lengths of the arriving waves can then be read off on the scale by adjusting the wave-meter circuits to give maximum sound in the telephone.

The cymometer or other wave meter can then be employed to measure the decrement of the oscillations in the receiving antenna as follows :—

The first step is to plot a resonance curve, as already shown, by setting out as ordinates the value of the mean-square current (J^2) in the cymometer circuit corresponding to various values of the natural frequency (n) of that circuit for various settings of the capacity and inductance within such limits that n does not differ from the resonance frequency N by more than 5 per cent. Then if J_r^2 is the mean-square value of the maximum or resonance current in the cymometer circuit, and δ_2 is the decrement per semi-period of that circuit, and if δ_1 is the decrement of the oscillations in the antenna, we have by the usual Bjerknes formula—

$$\delta_1 + \delta_2 = \pi\left(1 - \frac{n}{N}\right)\sqrt{\frac{J^2}{J_r^2 - J^2}} \quad . \quad . \quad . \quad . \quad (12)$$

Assuming, then, that the resonance curve is drawn with J^2 as ordinates and n as abscissæ, we may select various values of n and J^2, and substitute them in the above formula, provided that n is within 5 per cent. of N. We may shorten the calculation by taking $n = \frac{95}{100}N$ and $1 - \frac{n}{N} = \frac{1}{20}$, and determine the value of J^2, corresponding to this value of n.

Again, since the decrement of the cymometer circuit is given by the expression $\delta_2 = \frac{R'}{4nL'}$, where R′ is the high frequency resistance of

that circuit and L' is its inductance corresponding to the frequency n, then for those types of wave meter in which L' is either constant or varies proportionately to R', we have $\delta_2 = \frac{C}{n}$, where C is some constant for the instrument which can be determined by experiment.

Accordingly, the semi-period decrement of the oscillations in the sending antenna is given by the expression—

$$\delta_1 = \frac{\pi}{20}\sqrt{\frac{1}{A^2 - 1}} - \frac{C}{n} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where A^2 is the ratio of the mean-square values of the resonance current and the current corresponding to a frequency n which exist in the wave-meter circuit, n differing by 5 per cent. from the resonance frequency, and C being an instrumental constant of the wave meter, viz. the value of $\frac{R'}{4L'}$ for that setting of the instrument corresponding to the frequency n.

The receiving appliance must consist of an inductance coil of adjustable inductance, and a coil in series with it which forms the primary of an oscillation transformer the secondary circuit of which is movable so as to vary over wide limits the coupling of the two circuits. The secondary circuit is completed by a condenser of variable capacity, and the terminals of this capacity are connected also through a rectifying contact, such as the molybdenite, copper point and a high-resistance telephone in series with the latter.

The first step is to determine the ratio of the mean-square values of the resonance currents in the secondary circuit of the transformer when the secondary is set with various couplings, or at various distances from the primary. This can be done by sending constant oscillations through the primary circuit, and employing a low resistance hot wire ammeter in the secondary circuit, or else a high-resistance galvanometer in place of the telephone in series with the rectifying contact, the two being placed as a shunt across the condenser. In the experiment we are really obtaining the value of the square of the coupling $\left(\frac{M^2}{LN}\right)$ for the two circuits of the transformer. Having done this we replace the telephone on the detector circuit and adjust the receiver to pick up the impinging waves of which it is desired to measure the decrement. The coupling of the two circuits of the transformer must then be reduced until the sound in the telephone just ceases to be heard. Let the mean-square current in the secondary circuit be then denoted by J_r^2.

The tuning is then altered by changing the capacity in the secondary circuit sufficiently to make its natural frequency differ by 5 per cent. from the resonance frequency. The coupling is then strengthened until the sound in the telephone is again just audible. Let the mean-square current in the secondary circuit be then denoted by J^2, and the resonance mean-square current for exact tuning at frequency N corresponding to that particular coupling be denoted by ${}_1J_r^2$. We may then assume that, $J_r^2 = J^2$, and we have

previously determined the ratio ${}_1J_r^2$ to J_r^2. Call this ratio a for the couplings in question. Then it follows that—

$$\frac{{}_1J_r^2}{J_r^2} = a = \frac{{}_1J_r^2}{J^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

and the decrement of the oscillation in the receiving antenna will be given by the same formula as before, viz.—

$$\delta_1 = \frac{\pi}{20}\sqrt{\frac{1}{a-1}} - \delta_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

To determine δ_2, or the decrement per semi-period of the secondary circuit of the oscillation transformer, a second set of readings must be taken in the same manner in which the decrement of the secondary circuit is artificially increased by the insertion in it of a fine wire of high resistance, r^1, the added decrement due to this is $\delta_2^1 = \frac{r^1}{4n_1 L_2}$, where n_1 is the frequency and L_2 the inductance of the secondary circuit at resonance. If then ${}_2J_r^2$ is the mean-square secondary current with this added resistance, and if ${}_3J_r^2$ is the current for the same coupling with the resistance r^1 cut out, then by equation (9) we have—

$${}_3J_r^2\delta_2(\delta_1 + \delta_2) = {}_2J_r^2(\delta_2 + \delta_2')(\delta_1 + \delta_2 + \delta_2') \quad . \quad . \quad (16)$$

If the coupling in this last experiment is so arranged that ${}_2J_r^2$ is a current just audible in the telephone, we can say that ${}_2J_r^2 = J_r^2$, and the ratio of ${}_3J_r^2$ to $J_r^2 = \beta$ is known from the previous calibration.

Hence from equation (15) and (16) we can determine δ_1.

The process is rendered much more simple in those cases in which the current in the receiving antenna is large enough to affect directly a sensitive thermal-micro ammeter such as Mr. Duddell's instrument, for we have then no difficulty in determining the ratio $\frac{J_r^2}{J^2}$ for the two frequency settings of the receiver.

PART III.—ELECTRIC WAVE OR RADIO-TELEGRAPHY

CHAPTER VII

THE EVOLUTION OF ELECTRIC WAVE TELEGRAPHY

1. **Early Ideas and Experiments.**—The reader who desires to study the earlier attempts to conduct practical telegraphy without connecting wires must consult books more especially devoted to the historical side of the subject.[1]

From the earliest days of electric telegraphy, inventors had their attention directed to the problem of dispensing in part or entirely with continuous interconnecting wires. In 1838, Steinheil of Munich, acting on a suggestion made by Gauss, demonstrated that the earth could perform the function of a return for a telegraphic circuit, and thus made one of the most important contributions to practical telegraphy.

He seems, moreover, to have anticipated that in time improvements might be effected by which the necessity for any metallic circuit at all would be removed.[2] From the date of that suggestion the notion of telegraphy without wires may be said to have been ever present to the minds of telegraphic engineers.

The necessity for finding some solution of the problem of wireless telegraphy increased as the art of electric telegraphy itself extended, even if it were only to enable telegraphists to bridge over some short break or interval in a metallic circuit. Suffice it here to say that if we exclude the method depending on the employment of electromagnetic waves, the processes which had been previously found feasible or had been suggested were based upon—

(i.) The conduction of electric currents through the moist earth or the water of rivers, lakes, or seas. This method particularly engaged

[1] We may particularly refer the reader to the excellent work by Mr. J. J. Fahie, "A History of Wireless Telegraphy" (Blackwood & Sons, London and Edinburgh).

[2] See Fahie's "History of Wireless Telegraphy, 1838–1899," 1899, p. 4. (Blackwood & Co.); also Fahie's "History of Electric Telegraphy to the Year 1837," pp. 343–348, for the history of the *earth return* in telegraphy.

Although Stenheil was not the first to employ or suggest the use of an earth return for completing an electric circuit, he was the first to apply it in practical telegraphy, and to realize its importance.

See also Steinheil, "Ueber Telegraphie, insbesondere durch galvanische Kräfte." Munich, 1838.

Interesting quotations from Steinheil's writings are given in Mr. Fahie's book on wireless telegraphy.

the attention of Morse, Lindsay, Trowbridge, Preece, Rathenau, Strecker, Wilkins, and Melhuish.

(ii.) Electromagnetic induction between parallel metallic conductors, either complete circuits or circuits including earth returns. Suggested and studied by Trowbridge, Preece, Stevenson, and Lodge.

(iii.) A combination of methods (i.) and (ii.). Made into a practical system chiefly by the labours of Sir William Preece, aided by the British Postal Telegraph Engineers.

(iv.) Electrostatic induction between conductors separated by a greater or less distance. Brought to a working success by Edison, Gilliland, Phelps, and W. Smith, as a means of communication with moving railway trains.

The reader wishing to have some information with regard to the earlier researches of the above-named inventors may be referred to the following original papers, as well as to the "History of Wireless Telegraphy," by Mr. J. J. Fahie above mentioned.

J. Trowbridge, "The Earth as a Conductor of Electricity," *American Acad. Arts and Sciences*, 1880.

W. H. Preece, "Recent Progress in Telephony," *British Association Report*, 1882.

W. H. Preece, "Electric Induction between Wires and Wires," *British Association Reports*, 1886 and 1887.

W. H. Preece, "Electric Signalling without Wires," *Journal Soc. of Arts*, February 23, 1894.

W. H. Preece, "Signalling through Space without Wires," *Proc. Roy. Inst. Lond.*, 1897, vol. xv. p. 467.

W. H. Preece, "Ætheric Wireless Telegraphy," *Proc. Inst. Elec. Eng. Lond.*, 1898, vol. xxvii. p. 869.

O. J. Lodge, "Magnetic Space Telegraphy," *Proc. Inst. Elec. Eng.*, 1899, vol. xxvii. p. 799.

In many cases suggestions were put forward which were based upon obviously erroneous ideas, and even embodied in patent specifications without being subjected to critical trial. Nevertheless, the best of the methods above classified had only enabled comparatively short distances to be covered. Even the most effective of them, viz. the method involving both conduction through the soil or water and electromagnetic induction between parallel wires, was extremely limited in its applicability by reason of the necessity for employing two parallel metallic wire circuits almost as long as the distance to be bridged.

A new era dawned when the scientific investigations commenced which finally placed us in possession of the principal facts connected with the generation and detection of electromagnetic waves, or as they are more shortly called, electric waves.

Maxwell's profound speculations and mathematical researches resulted, as we have seen, in the enunciation in 1865 of his famous electromagnetic theory of light. This theory, owing to its abstract nature, was not at first fully appreciated. Hertz's discoveries and investigations, published in 1888, cast a flood of light upon its meaning, and whilst opening up a wide and promising field for experimental investigation, gave such enforcement to Maxwell's theory that it at once commanded general attention.

The matter, however, which chiefly interested physicists were the

properties of the long waves generated in the æther by Hertzian methods, and the similarity between the effects connected with them and familiar optical phenomena. Hence a rapidly accumulated mass of experimental evidence was obtained, tending to show that luminous radiation is electromagnetic in nature. These electro-optic phenomena were sedulously studied, and physical optics became, as it were, a department of electromagnetism.

When any new field of discovery or invention is thus laid open, it invites the attention of two classes of minds. There are those who are chiefly drawn to its cultivation by a desire to increase purely scientific knowledge, and to explore the mysteries involved, regardless of any particular practical utility they may possess. On the other hand, there are others to whom this pursuit of novel facts or effects, or the unravelling of complicated phenomena, or the construction of new theories, does not appeal. They are impelled to look at once for applications of the new knowledge which will minister to the convenience or mitigate the troubles of mankind. Probably in neither case is a more personal motive entirely absent, but whilst some minds regard the discovery of new physical facts or laws as an end in itself, others regard them only as a means to an end, and invent rather than discover or explore. The general non-scientific public are, however, prone to attach more importance to the so-called applications than to the discoveries out of which they have grown. Hence the practical inventor or applier of scientific knowledge generally occupies in the public mind a more prominent position than the purely scientific investigator. Unless the latter has the good fortune to make some sensational discovery capable of immediate technical application, such as the Röntgen radiation, his work will seldom attract notice outside of a limited circle of experts. So it was in the case of the field of investigation laid open by Hertz. Between 1888 and 1895 a host of scientific workers in various lands gathered in a rich harvest of scientific knowledge concerning the properties and powers of electromagnetic waves. The non-scientific public concerned itself but little with these results.

In 1892 Nikola Tesla captured the attention of the whole scientific world by his fascinating experiments on high frequency electric currents. He stimulated the scientific imagination of others as well as displayed his own, and created a widespread interest in his brilliant demonstrations.

Amongst those who witnessed these things no one was more able to appreciate their inner meaning than Sir William Crookes. More than twenty years previously he had explored with wonderful skill and insight the phenomena of electrical discharge in high vacua, and had produced the instrument which subsequently produced the Röntgen rays. He allowed a trained scientific imagination to busy itself with the recent discoveries, and he wrote a now well-known article "On some Possibilities of Electricity" in the *Fortnightly Review* for February, 1892 (p. 173), in which he endeavoured to forecast some of the applications of high frequency electric currents and of Hertzian waves.

In this outlook into the future he clearly discerned the coming of a new form of wireless telegraphy based on an application of Hertz's

discoveries to the communication of intelligence from place to place. In the course of the paper Sir William Crookes made a cryptic reference to experiments in this direction he had witnessed "some years ago," which were subsequently explained to refer to unpublished investigations by the late Professor D. E. Hughes, in which signals were sent "a few hundred yards," without connecting wires, by the aid of a telephone. No details of the experiments were given, or any hint of how the result was obtained. For the purposes of patent litigation this notable essay has been put forward as an anticipation of subsequent practical work. It is necessary, however, to keep clearly in mind the true meaning of "invention." Invention does not consist in displaying a few brilliant and original ideas. Neither does it consist in outlining a certain set of requirements and broadly defining the means by which certain ends may be attained. Invention consists in overcoming the practical difficulties of the new advance, not merely talking or writing about the new thing, but in *doing it*, and doing it so that those who come after have had real obstacles cleared out of their way, and have a process or appliance at their disposal which was not there before the inventor entered the field. In most cases, however, the removal of the obstacles which block the way is not entirely the work of one person. The fort is captured only after a series of attacks, each conducted under a different leader. In these cases the inventor who breaks down the last obstruction or leads the final assault is more particularly associated in the public mind with the victory than are his predecessors, though his intrinsic contribution may not be actually of greater importance.

There are other cases, however, in which, prior to the work of one man, we can find no actual achievement, although the end to be attained, and to some extent the character of the means to be used, are clearly recognized.

In the article to which reference is made we find much remarkable prognostication, but not a description of actual inventions.

It emphasized, in fact, how much at that date (1892) yet remained to be done. Speaking of electromagnetic waves and their properties, Sir William Crookes says (*loc. cit.*):—

"Here is unfolded to us a new and astonishing world, one which it is hard to conceive should contain no possibilities of transmitting and receiving intelligence.

"Rays of light will not pierce through a wall, nor, as we know only too well, through a London fog. But the electrical vibrations of a yard or more in wave length of which I have spoken will easily pierce such mediums, which to them will be transparent. Here, then, is revealed the bewildering possibility of telegraphy without wires, posts, cables, or any of our present costly appliances. Granted a few reasonable postulates, the whole thing comes well within the realms of possible fulfilment. At the present time experimentalists are able to generate electrical waves of any desired wave-length from a few feet upwards, and to keep up a succession of such waves radiating into space in all directions. It is possible, too, with some of these rays, if not with all, to refract them through suitably shaped bodies acting as lenses, and so direct a sheaf of rays in any given direction; enormous lens-shaped masses of pitch and similar bodies have been used for this purpose. Also an experimentalist at a distance can receive some, if not all, of these rays on a properly constituted instrument, and by concerted signals messages in the Morse code can thus pass from one operator to another. What, therefore, remains to be discovered is—firstly, simpler and more certain means of generating electrical rays of any desired wave-length, from the shortest, say of a few feet in length, which will easily pass through buildings and fogs, to

those long waves whose lengths are measured by tens, hundreds, and thousands of miles; secondly, more delicate receivers which will respond to wave-lengths between certain defined limits and be silent to all others; thirdly, means of darting the sheaf of rays in any desired direction, whether by lenses or reflectors, by the help of which the sensitiveness of the receiver (apparently the most difficult of the problems to be solved) would not need to be so delicate as when the rays to be picked up are simply radiating into space in all directions, and fading away according to the law of inverse squares.

"I assume here that the progress of discovery would give instruments capable of adjustment by turning a screw or altering the length of a wire, so as to become receptive of wave-lengths of any preconcerted length. Thus, when adjusted to 50 yards, the transmitter might emit, and the receiver respond to, rays varying between 45 to 55 yards, and be silent to all others. Considering that there would be the whole range of waves to choose from, varying from a few feet to several thousand miles, there would be sufficient secrecy, for curiosity the most inveterate would surely recoil from the task of passing in review all the millions of possible wave-lengths on the remote chance of ultimately hitting on the particular wave-length employed by his friends whose correspondence he wished to tap. By 'coding' the message even this remote chance of surreptitious straying could be obviated.

"This is no mere dream of a visionary philosopher. All the requisites needed to bring it within the grasp of daily life are well within the possibilities of discovery, and are so reasonable and so clearly in the path of researches which are now being actively prosecuted in every capital of Europe that we may any day expect to hear that they have emerged from the realms of speculation into those of sober fact. Even now, indeed, telegraphing without wires is possible within a restricted radius of a few hundred yards, and some years ago I assisted at experiments where messages were transmitted from one part of a house to another without an intervening wire by almost the identical means here described."

The above vague reference to experiments on telegraphy without wires over a short distance was at a later date illuminated by the account given by Professor D. E. Hughes himself, of the precise nature of these hitherto undescribed experiments.[3] In the course of his work on the microphone, Professor D. E. Hughes had occasion to notice the wonderful sensitiveness of a "microphonic" or loose joint between conductors, and its variation of resistance under impacts, such as those of sound waves. He included such an "imperfect contact" in series with a voltaic cell and a telephone, and found that the resistance of certain kinds of contact was effected by electric sparks at a distance. Using a contact between carbon and steel, he no doubt constructed some form of self-restoring coherer, and made the important discovery that the discharge of a Leyden jar at a distance caused a sudden variation in its electrical resistance, and hence a sound in the telephone included in its circuit.

Professor D. E. Hughes stated in a letter addressed to Mr. Fahie, on April 29, 1899 (*loc. cit.*), that he showed these experiments in December, 1879, to Sir W. H. Preece, Sir William Crookes, Sir W. Roberts-Austen, Professor W. G. Adams, and Mr. W. Grove; also in February, 1880, to Mr. Spottiswoode, then president of the Royal Society, and to Professor Huxley, and Sir George Gabriel Stokes, the secretaries. In addition, he exhibited them to Sir James Dewar and Mr. Lennox. He was apparently discouraged from publishing the results at the time by finding that Sir George Stokes considered they were due to ordinary electromagnetic induction. It is, however, clear from the statements of Professor Hughes himself in 1899 that he had

[3] See a letter by Prof. D. E. Hughes in *The Electrician*, May 5, 1899, vol. 43, p. 40.

discovered (but not announced) in 1879 a number of facts afterwards rediscovered by Professor E. Branly in Paris in 1891, and he had, in fact, been using a self-restoring carbon-iron coherer in series with a telephone which was affected up to a distance of a few hundred yards by the electromagnetic waves created by an electric spark. If at the time he had publicly placed these observations on record, he would undoubtedly have anticipated some at least of Branly's work, but much remained to be done, which was subsequently done by Hertz and by Marconi, before electric wave wireless telegraphy, in any true sense of the word, could be translated from dream to fact.

Four years passed by, however, without any fulfilment of Crookes's scientific prophecy, although the most eminent physicists continued to work at the subject.

On January 1, 1894, the scientific world heard with profound regret of the death of Hertz.

On Friday, June 1, 1894, Sir Oliver Lodge delivered a memorial lecture on "The Work by Hertz," in the Royal Institution, London.

This lecture was remarkable in many ways. It gave many persons the opportunity of seeing, for the first time, striking experiments performed with Hertzian waves. The lecturer made use of a modified Branly's metallic filings tube, and also of a loose or imperfect metallic contact of his own invention, as a means of detecting the electric waves, and he gave to these devices the name *coherer*, by which they have since been known.

The tube was a glass tube loosely filled with iron borings and closed at the ends with metal plugs or caps. It is represented about one-third of full size in Fig. 3 of Chapter VI. The other form of coherer was a loose or microphonic contact between two pieces of metal, the pressure of which could be adjusted so that the junction offered too great a resistance to pass the current from a single cell, but *cohered* when electric waves fell upon it. In both cases the tapping back or decoherence was effected by hand after each experiment.

Experiments on the reflection, refraction, and polarization of these electric waves were shown, and their passage through stone walls from room to room. Yet, although replete with interest, the lecture, as originally delivered, contained not even a hint of a possible applications of these electromagnetic waves to telegraphy. The lecturer throughout fixed the attention of the audience on the similarity between the effects obtainable with these waves and those better known effects produced by rays of light.

It was, in fact, an experimental demonstration of the undulatory character of the electromagnetic radiation from an oscillator, and of the electromagnetic nature of ordinary light.

Subsequently the lecture was published as a book, the first edition of which bore the title, "The Work of Hertz and some of his Successors."[4]

These experiments and some variations of them were repeated at the meeting of the British Association at Oxford in the following autumn, but here again no mention of the application of these waves to telegraphy was made, the object of the experiments being to

[4] In later editions issued after 1896 the title was changed to "Signalling across Space without Wires."

illustrate an electrical theory of vision, and to expound the properties of the electric waves.[5]

It is highly probable that these articles and lectures, bringing home so forcibly the power of an electric spark to affect or make a deflection of a galvanometer at a distant place, must have turned the thoughts of many ingenious persons to its utilization as a means of sending telegraphic signals. Subsequently we were informed that the matter had begun to occupy the minds of Dr. A. Muirhead, Admiral Sir H. B. Jackson (then Captain in the Royal Navy), and Professor R. Threlfall, and perhaps many more.

Amongst others, Professor A. S. Popoff, Professor in the Imperial Torpedo School in Cronstadt, Russia, directed his attention to the subject, attracted to it by Lodge's lecture, and desirous, as he says, of repeating the experiments both for lecture purposes, and for registering electrical perturbations taking place in the atmosphere. His apparatus and wave detector have already been described (see Chap. VI. § 3), as well as the publication of his description of them, and experiments conducted with them in January, 1896, in the *Journal of the Physico-Chemical Society of St. Petersburg.*

It is beyond question, however, that the use he made of his apparatus was not the communication of intelligence to a distance, but for studying atmospheric electricity. The observations were made at the Institute of Forestry, St. Petersburg. Popoff says—

"Upon the building of the Institute, amongst other arrangements made for observing the direction and force of the wind, there was a small wooden mast about 4 sajen (28 feet) higher than the rods carrying the anemometers and weathercocks, and which was furnished at the top with an ordinary lightning point and rod. This lightning rod, by means of a wire carried first on the wood of the mast, and further stretched across the yard on insulators into the meteorological observatory, was connected with the apparatus at the point A (Fig. 2), whilst the point B was connected to a wire which served as an earth conductor or connection for the other meteorological apparatus, and was connected to the water-supply pipes. The registering arrangements consisted of an electromagnet, to the armature of which there was attached a Richard pen writing on a Richard recording cylinder, making one revolution per week. It was found that the apparatus responded by a ring of the bell to every closing of an electric circuit which was recording observations of the direction and force of the wind, since electric oscillations were then set up in the conductors connected with the apparatus by the common conductor leading to the earth plate. In order to distinguish these marks from the others made by atmospheric electricity, the observers, who produced the ringing, made a note each time on the cylinder. This action upon the apparatus was, however, useful for the purpose of being sure that it continued in good order."

That this primary object was not telegraphy is shown by the paragraph with which he concludes his paper (*loc. cit.*). He says—

"In conclusion, I may express the hope that my apparatus, with further improvements, may be adapted to the transmission of signals to a distance by the aid of quick electric vibrations as soon as a means for producing such vibrations possessing sufficient energy is found."

We are left, then, with this unquestionable fact that at the beginning of 1896, although the most eminent physicists had been occupied for nine years in labouring in the field of discovery laid open by

[5] See *The Electrician*, August 17, 1894, vol. 33, p. 458. For pictures of the Lodge apparatus exhibited at Oxford, see *The Electrician*, vol. 39, p. 687.

Hertz, and although the notion of using these Hertzian waves for telegraphy had been clearly suggested, no one had overcome the practical difficulties, or actually given any exhibition in public of the transmission of intelligence by alphabetic or telegraphic signals by this means. The appliances in a certain elementary form existed, the advantages and possibilities of electric wave telegraphy had been pointed out, but no one had yet conquered the real practical difficulties, and exhibited the process in actual operation.

2. Marconi's Work, 1895-1898.—Meanwhile, a young investigator had been busy in Italy. Guglielmo Marconi was born at Bologna on April 25, 1874, and very early displayed an original and inventive mind. He studied physics under Professor Rosa of the Leghorn Technical School, and made himself acquainted with the published writings of Professor Righi of the University of Bologna, whose valuable work on electromagnetic radiation was well known.

When little more than twenty years of age, Marconi had not only acquired much knowledge of Hertzian wave research, but he had clearly formed the intention of devoting himself to its utilization for effecting wireless telegraphy.

On his father's estate at the Villa Griffone, near Bologna, he began experimenting in June, 1895, with Hertzian waves, using an ordinary spark induction coil, and making for himself experimental coherers or various forms of the Branly tube. Before long he originated an important improvement. Instead of employing the Hertzian form of radiator, he connected one terminal of the secondary circuit of his induction coil to a metal plate or net laid on the ground, and the other by a wire to a metal can or cylinder, placed on the summit of a pole. The spark balls were kept at such a distance than on closing the primary circuit of the coil an oscillatory spark passed between them. At the receiving end he similarly connected a metallic filings sensitive tube between an earth plate and an insulated conductor or capacity. He then began systematically to examine the relation between the distance at which the spark could affect his coherer and the elevation of his cans or cylinders above the ground. This brought him speedily to the discovery that the higher the cans the greater the distance over which he could work.

Thus in 1895 he was using cubes of tin about 1 foot in the side as elevated conductors or capacities, and found that when placed on the tops of poles 2 ms. high he could receive signals at 30 ms. distance, and when placed on poles 4 ms. high at 100 ms., and at 8 ms. high at 400 ms. With larger cubes of 100 cms. side fixed at a height of 8 ms. Morse signals could be transmitted 2400 metres, or $1\frac{1}{2}$ miles all round.

Before this time, however, he had improved the Branly metallic filings tube, and produced his own nickel-silver filings sensitive tube already described (see Chap. VI. Fig. 4). He had combined this sensitive and regularly acting improved coherer with an electric-tapping arrangement, but with more careful insight into the conditions to be fulfilled and a greater range of adjustment than previous workers.

He added also to the filings tube a pair of inductances or choking coils, intended to prevent the electric oscillations passing through the

circuit in parallel with the tube, and compel them to expend their energy on the tube itself. He placed in series with the tube a single voltaic cell and a sensitive relay, and employed the relay to actuate a Morse printing instrument worked by a separate set of cells. In addition, he placed shunt circuits across the tapper break contacts and relay contacts to prevent sparking, and therefore disturbances of the sensitive tube by local effects.

Finally, he mounted the whole receiving arrangement on a board and enclosed the tube, tapper, and relay in a metallic box to shield them from the direct action of electric sparks made in their vicinity.

In the primary circuit of the induction coil at the transmitting end he placed a Morse sending key, and he connected the secondary terminals to the earth and to an elevated conductor as described. At the receiving end he connected, in the early experiments, one end of the coherer tube to an earth plate, and the opposite terminal to an elevated capacity. Lastly, he made such adjustments of the tapping arrangements that when a short series of oscillatory sparks were made at the induction coil by just depressing the Morse key in its primary circuit for one moment, the combination at the receiving end printed a *dot* on the Morse tap, and when the key was depressed for a longer time it printed a *dash*. In this manner the two signals required for forming an alphabet on the Morse code were obtained, and letters and words could be printed on the tape at the receiving end by properly handling the key at the transmitting end.

He employed at first the ball discharger of Professor Righi, which consisted of four solid brass balls, the two larger central ones being separated by a certain small interval, and the space between filled with vaseline oil kept in position by a non-conducting jacket or membrane.

In some experiments Marconi placed the discharge balls in the focal line of a cylindrical parabolic mirror, and the receiver in the focus of another similar mirror, using, for the purpose of collecting the wave energy, two metal strips or rods, attached to the extremities of the coherer tube.

In 1896 he came to England with this apparatus, and on June 2, 1896, he applied for a British patent, No. 12,039, for the invention, which was duly granted. The complete specification was filed March 2, 1897.[6]

In July, 1896, he introduced his invention and new method of telegraphy to the notice of Sir William Preece, then engineer-in-chief to the British Government Telegraph Service, who had for the previous twelve years interested himself in the development of wireless telegraphy by the inductive-conductive method.

On June 4, 1897, Sir W. H. Preece gave a lecture to a large audience at the Royal Institution in London on "Signalling through Space without Wires." [7] In this lecture, after expounding older and other methods, he devoted considerable time to exhibiting and

[6] The United States of America equivalent patent was numbered originally No. 586,193, applied for December 7, 1896, and issued July 13, 1897. After amendment it was reissued as No. 11,913, granted June 4, 1901.

[7] See *The Electrician*, June 11, 1897, vol. 39, p. 216; also *Proc. Roy. Inst. Lond.*, 1897, vol. xv. p. 467.

explaining the Marconi apparatus, and spoke of it in the following terms :—

"In July last Mr. Marconi brought to England a new plan. Mr. Marconi utilizes electric or Hertzian waves of very high frequency. He has invented a new relay which for sensitiveness and delicacy exceeds all known electrical apparatus. The peculiarity of Mr. Marconi's system is that, apart from the ordinary connecting wire of the apparatus, conductors of very moderate length only are needed, and even these can be dispensed with if reflectors are used."

Testifying to its practicability as a telegraphic method, Sir William Preece said—

"Excellent signals have been transmitted between Penarth and Brean Down, near Weston-super-Mare, across the Bristol Channel, a distance of nearly nine miles. On Salisbury Plain Mr. Marconi covered a distance of four miles."

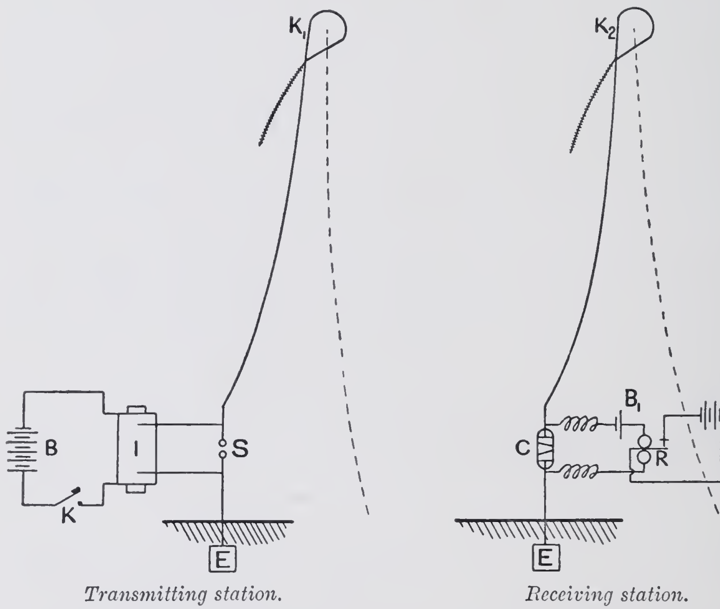


FIG. 1.—Marconi's Apparatus for Wireless Telegraphy in 1896. B, battery; I, induction coil; S, spark balls; K, sending key; E, earth plate; K_1, K_2, kites upholding aerial wires; C, coherer; R, relay; M, Morse printing instrument; B_1, B_2, batteries.

As regards the means used, it was stated that up to a distance of four miles a 6-inch spark coil sufficed, but for greater distances a 20-inch spark coil had been employed. In these experiments the method with reflecting mirrors was tried, but the chief part was carried out by connecting one terminal of the coherer and the spark coil secondary circuit respectively to earth, and each of the other terminals to nearly vertical wires upheld by masts, these wires terminating sometimes in metal plates or cylinders, or else the wires were upheld by balloons or kites covered with tinfoil in the manner shown in diagram in Fig. 1.

The evidence at this date all goes to show that the highest authorities on the subject admitted the novelty of Marconi's telegraphic method and appliances.

One technical paper (the London *Electrician*), after a column and a half of editorial comment on the Preece lecture, ended by saying—

"Meanwhile we wish Mr. Marconi, his apparatus and experiments, all possible success, if only because the evolution from Maxwellian equations and Hertzian vibrations of a thoroughly practical system of telegraphy will prove an excellent object lesson on the value of pure research." [8]

Sir William Preece, at the conclusion of his lecture, combated the contention, which appears to have been raised, that Mr. Marconi had done nothing new, and said (*loc. cit.*)—

"He has not discovered any new rays; his receiver is based on Branly's coherer. Columbus did not invent the egg, but he showed how to make it stand on its end, and Marconi has produced from known means a new electric eye more delicate than any known electrical instrument, and a new system of telegraphy that will reach places hitherto inaccessible. . . . Enough has been done to prove and show that for shipping and lighthouse purposes it will be a great and valuable acquisition."

The news of these successful demonstrations spread abroad and excited great interest. Amongst those who had been giving attention to the utilization of Hertzian waves was Professor A. Slaby, one of the Engineering Professors in the Technical High School at Charlottenburg, Berlin, and he at once hurried to England to discover how Marconi had solved a problem that had hitherto baffled him (Professor Slaby).

After seeing and assisting in the experiments across the Bristol Channel, Professor Slaby wrote a magazine article on "The New Telegraphy," [9] and made the following remarks:—

"In January, 1897, when the news of Marconi's first successes ran through the newspapers, I myself was earnestly occupied with similar problems. I had not been able to telegraph more than one hundred metres through the air. It was at once clear to me that Marconi must have added something else—something new—to what was already known, whereby he had been able to attain to lengths measured by kilometres. Quickly making up my mind, I travelled to England, where the Bureau of Telegraphs was undertaking experiments on a large scale. Mr. Preece, the celebrated engineer-in-chief of the General Post Office, in the most courteous and hospitable way, permitted me to take part in these; and in truth what I there saw was something quite new. Marconi had made a discovery. He was working with means the entire meaning of which no one before him had recognized. Only in that way can we explain the secret of his success. In the English professional journals an attempt has been made to deny novelty to the method of Marconi. It was urged that the production of Hertz rays, their radiation through space, the construction of his electrical eye—all this was known before. True; all this had been known to me also, and yet I was never able to exceed one hundred metres.

"In the first place, Marconi has worked out a clever arrangement for the apparatus which by the use of the simplest means produces a sure technical result. Then he has shown that such telegraphy (writing from afar) was to be made possible only through, on the one hand, earth connection between the apparatus and, on the other, the use of long extended upright wires. By this simple but extraordinarily effective method he raised the power of radiation in the electric forces a hundredfold."

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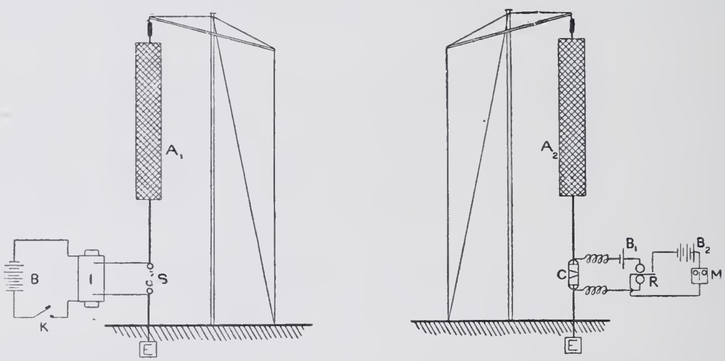
[8] See Editorial Notes, *The Electrician*, vol. 39, p. 208.

[9] See Dr. A. Slaby on "The New Telegraphy," *The Century Magazine*, April, 1898, vol. 55, p. 867.

The two and a half years between June, 1896, and December, 1898, were occupied by Marconi with numerous public demonstrations of the utility of his system of wireless telegraphy. Space cannot be afforded for a detailed history, but the general facts are as follows :—

The autumn of 1896 was occupied with experiments carried out before representatives of the British Government Postal Telegraph Department, and communication was established over a distance of 2 miles. Tests were also carried out in the presence of the Navy and Army representatives (Captain Jackson, R.N., and Major Carr, R.E.), on Salisbury Plain, during the month of March, 1897, when transmission over a distance of eight miles was demonstrated. In May, 1897, the experiments already described, between Penarth and Weston-super-Mare, were made across the Bristol Channel, a distance of nine miles. In July, 1897, Marconi undertook demonstrations for the Italian Government at Spezzia, in Italy, and covered a distance of 12 miles between warships. Communication was then set up by



Transmitting station. *Receiving station.*

FIG. 2.—Marconi's Apparatus for Wireless Telegraphy as used in 1896–98. A_1, A_2, strips of wire netting constituting the antennæ, upheld by insulators at the top of masts. The remaining letters refer to apparatus as mentioned under Fig. 1.

him between Alum Bay, in the Isle of Wight, and Bournemouth, England, a distance of about 14 miles over sea, and the working of the system was inspected by the author, in April, 1898. Marconi was at that time using as the transmitter a 10-inch spark induction coil, and a discharger consisting of four balls of brass, each about 2 inches in diameter, spaced slightly apart in an ebonite frame.

One of the outer balls was connected by a thick wire to an earth plate, and the other outer ball by a wire to an insulated strip of wire netting about 120 feet in length, which was upheld by an ebonite insulator attached to a sprit hauled up to the top of a 120-foot mast (see Fig. 2). These balls were also in connection with the secondary terminals of the induction coil, and the four brass discharge balls were set with air gaps about $\frac{1}{4}$ inch, or 5 to 6 mm., long between the balls. In the primary circuit of the induction coil was placed a massive Morse key with heavy platinum contacts. Marconi had at that time abandoned the use of the Righi discharger with balls

in oil. The receiver used was exactly as already described. With this apparatus telegraphic messages were sent in Morse code at about a rate of 12 to 15 five-letter words per minute. The working of this Isle of Wight to Bournemouth plant was inspected by many notable men, *e.g.* Lord Tennyson, Lord Kelvin, and others; and Lord Kelvin gave practical expression to his opinion that it was already in a commercial condition by paying for a message sent by him to Sir William Preece at the General Post Office, London, on June 3, 1898.

In May, 1898, communication was established for the Corporation of Lloyds between Ballycastle and the Lighthouse on Rathlin Island in the North of Ireland, the distance being 7·5 miles.

In July, 1898, the Marconi telegraphy was employed to report the results of yacht races at the Kingstown Regatta for the *Dublin Express* newspaper. A set of instruments were fitted up in a room at Kingstown, and another on board a steamer, the *Flying Huntress*. The aerial conductor on shore was a strip of wire netting attached to a mast 40 feet high, and several hundred messages were sent and correctly received during the progress of the races. The distances were from 5 to 20 miles.

At this time His Majesty King Edward VII., then Prince of Wales, had the misfortune to injure his knee, and was confined on board the royal yacht *Osborne* in Cowes Bay. Mr. Marconi fitted up his apparatus on board the royal yacht by request, and also at Osborne House, Isle of Wight, and kept up wireless communication for three weeks between these stations. The shore mast was 105 feet high, and the wire on board the yacht 83 feet high. The distances covered were small; but as the yacht moved about, on some occasions high hills were interposed, so that the aerial wires were overtopped by hundreds of feet, yet this was found to be no obstacle to communication.

The success of these demonstrations led the Corporation of Trinity House to afford an opportunity for testing the system in actual practice between the South Foreland Lighthouse, near Dover, and the East Goodwin Lightship, on the Goodwin Sands. This installation was set in operation on December 24, 1898, and proved to be not only most successful, but of the greatest practical value. It was shown that when once the apparatus was set up it could be worked by ordinary seamen with very little training.

At the end of 1898 electric wave telegraphy had thus been established by Marconi on a practical basis. He had demonstrated its utility, especially for communication between ship and ship and ship and shore, a work which could not be accomplished by any other system.[10]

It had been shown that the advantages were as follows:—

(i.) It worked as well by night as by day, and in bad weather, fogs, or storms, as well as in fair weather; provided that the proper insulation of the aerial wire or elevated conductor was maintained.

(ii.) In certain electrical conditions of the atmosphere, and during thunderstorms, some difficulty was usually found in working, owing

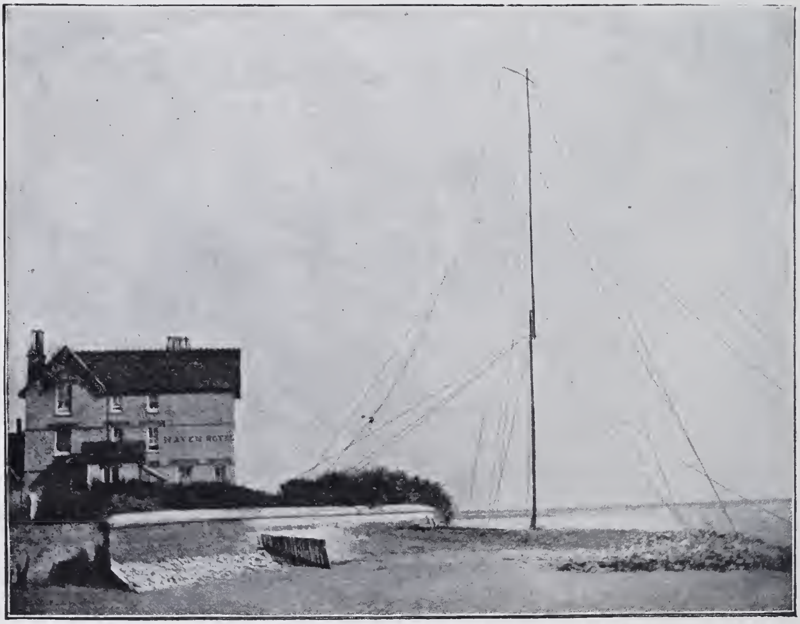
[10] A summary of his work on wireless telegraphy up to the beginning of 1899 is given in a paper read by Mr. Marconi to the Institution of Electrical Engineers on March 2, 1899. See *Journal of the Inst. Elec. Eng.*, 1899, vol. 28, p. 273.

to the atmospheric discharges affecting the sensitive tube, and therefore making stray marks on the Morse tape of the printer, but seldom sufficient to interrupt communication altogether.

(iii.) The interposition of high hills, trees, or the curvature of the earth did not prevent communication, though slightly affecting the power required. It worked particularly well over sea surface, and between ships and shore stations.

(iv.) The apparatus could be set up and handled by any ordinary telegraphist, and the record was made on paper strip in the usual Morse code.

(v.) It easily covered distances far beyond those feasible or attained by other systems of wireless telegraphy.



By kind permission of the Marconi Wireless Telegraph Company.

Fig. 3.—The Haven Hotel, Sandbanks, Poole, and Wireless Telegraph Mast. At this station much of Mr. Marconi's research work on wireless telegraphy has been carried out since 1898.

(vi.) Lastly, the apparatus required was by no means costly, and, with the exception of the mast required for upholding the aerial wire, it occupied but little space, and was particularly adapted for use on board ship.

The general appearance of the collected sending and receiving apparatus required inside the station or cabin is shown in Fig. 10.

3. Marconi's Improvements in 1898 and 1899.—Marconi was desirous of working over still greater distances than those already covered, but the difficulties of erecting masts for elevating the aerial conductor beyond a certain height were considerable. A mast 100

or 120 feet high is a comparatively simple thing to set up. It can be erected in three sections, and the aerial wire can be supported by insulators from a cross sprit at the top (see Fig. 3).

At the beginning of 1899, masts 120 to 140 feet high were employed, and an aerial wire consisting of a stranded copper wire 7/20 or 7/22 (generally an indiarubber insulated wire) was used. Very often a cylinder of wire netting was attached at the top or insulated end, and sometimes two or more aerial wires in parallel were used. The insulators were round rods of ebonite, about 24 inches long and 1 inch in diameter. When using simple wires and the receiving and transmitting apparatus of the 1896–1898 type, Marconi had found that the maximum distance which could be covered seemed to increase

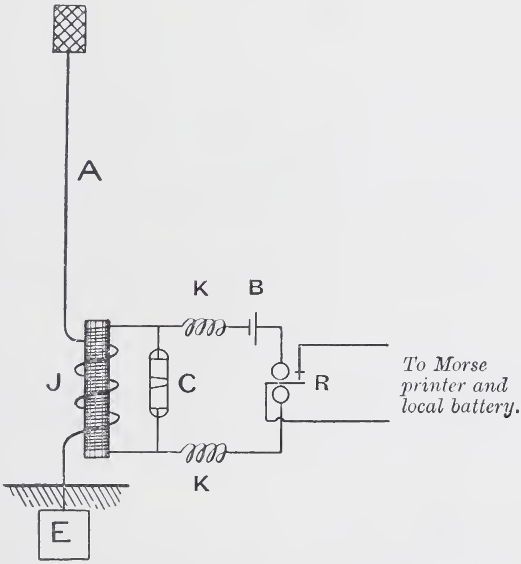


FIG. 4.—A, receiving antenna, or aerial wire, with capacity plate at summit; J, jigger, or oscillation transformer; C, coherer, or sensitive tube; E, earth plate; R, relay; B, relay cell; K, K, choking coils.

in proportion to the square of the height of the aerial wire, so that with aerials 100 feet high at each end the maximum working distance was four times that obtained with aerials 50 feet high.

He introduced, however, at this date an improvement into his receiving arrangements which had the result of increasing its sensitiveness. Instead of inserting the sensitive metallic filings tube or cymoscope directly between the earth plate and the bottom of the receiving aerial wire, an oscillation transformer of a particular form was interposed (see Fig. 4).

In considering the production of stationary electric oscillations in wires in Chap. IV., it has been explained that if a vertical wire is set up with its lower end in connection with an earth plate, then when the fundamental oscillation is set up in the wire we have a node of

potential and an antinode or maximum of current at the lower or earthed end of the aerial.

If, then, we cut this aerial wire near the earth and insert a coherer between the earth plate and the aerial wire, the production of oscillations in the wire only results in establishing a relatively small difference of potential between the terminals of the coherer. This instrument is, in fact, being employed in a very inefficient manner, and inserted in the wrong place. We shall see later on that Professor Slaby found another ingenious solution of this problem. Marconi, however, adopted the plan of inserting in the base of the aerial wire near the earth the primary coil of a small air core transformer, J, of a peculiar kind, the secondary terminals of which were connected to the sensitive tube, C (see Fig. 4). In this manner the large current existing near the base of the aerial was, so to speak, transformed into high voltage for use at the terminals of the coherer. To do this effectively, however, requires a special form of transformer. Lodge had previously suggested in a British patent specification the employment of a transformed oscillation for affecting the coherer so that it was operated by secondary oscillations, and not directly by those in the receiving rods.[11] Lodge, however, gave no details of construction, and from the diagram in his specification it is impossible to determine the dimensions and the nature of the circuits suitable for making a transformer which will be operative in any given case. Marconi discovered, after innumerable experiments, the proper form to give to such an oscillation transformer, and particularly described it in patent specifications and lectures.

Marconi's oscillation transformer, or "jigger," in one form consists of a glass tube about 1 cm. in diameter and 4 to 8 cms. in length. On this is wound a primary circuit consisting of a length of silk-covered copper wire, which may vary in diameter, according to circumstances, from No. 26 to No. 40 S.W.G. This coil is put on in one layer, or in two or more layers, which may be joined in parallel or in series.

The total length of primary wire may be from 3 to 20 feet or more, but is determined by the aerial used. The secondary circuit is wound over the primary, and is generally a silk-covered copper wire of size No. 36 or No. 40 S.W.G. It may have a length of 100, 150, or even 1000 feet or more, according to the wave length used. It was asserted to be an advantage to wind this secondary circuit in a peculiar manner, not putting it on in level layers, but bunching it in sections, each layer in each section consisting of a smaller number of turns than the preceding and inner layer. This mode of winding is indicated in the diagrams in Fig. 5, which are half-sections of various oscillation transformers, the thick black lines standing for layers of primary wire and the thinner lines for layers of secondary wire. The annexed tables give the numbers of the primary turns and the secondary turns in the various tapering bunches for two particular oscillation transformers described by Marconi in his first British Patent Specification on the subject.[12]

[11] See Lodge's British Patent, No. 11,575, of 1897.

[12] See British Patent Specifications, No. 12,326, of June 1, 1898; also No. 6982, of April 1, 1899, granted to G. Marconi and others.

Jigger No. 1. Primary.	Jigger No. 1. Secondary.	Jigger No. 2. Primary.	Jigger No. 2. Secondary.
2 layers of 160 turns each, in parallel	3 sections of 9, 11, 9 layers, with 150 45 40 45 40 39 40 35 37 35 30 35 30 25 33 25 20 29 20 15 25 15 12 21 17 5 15 14 10 5 turns respectively	2 layers of 160 turns each, in parallel	4 sections of 9 layers, with 40 | 80 | 40 35 | 35 | 35 | 35 30 | 30 | 30 | 30 27 | 27 | 27 | 27 23 | 23 | 23 | 23 20 | 20 | 20 | 20 15 | 15 | 15 | 15 10 | 10 | 10 | 10 5 | 5 | 5 | 5 turns respectively

This mode of winding the jigger in layers of gradually decreasing number of turns was later on found not to be of any marked utility and was abandoned in favour of a more simple form of cylindrical winding. The matter of practical importance is the ability to alter at pleasure the *coupling* of the two circuits, viz. the quantity $\frac{M}{\sqrt{LN}}$, where M is the coefficient of mutual inductance of the two circuits

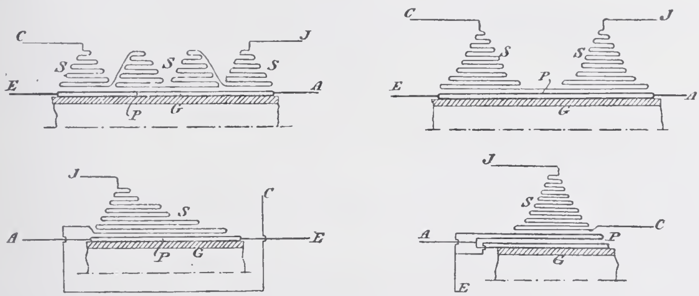


Fig. 5.—Half-sectional Diagrams illustrating Various Early Forms of Jigger, or Receiving Oscillation Transformer, used by Marconi. The fine zigzag lines denote layers of silk-covered wire, and the crossed line is the section of one side of a glass tube on which the wire is wound.

and L and N their self inductances. Hence in more modern types of jigger or oscillation transformer the coils are so arranged that their distances or *coupling* can be altered. If both coils are wound on cylindrical formers or tubes, one can be slid into or out of the other. If they are wound as flat spirals they can be fixed to two hinged boards or otherwise arranged so as to vary their distance.

In a third British Patent Specification (No. 25,186, of December 19, 1898) Marconi described an additional improvement. He divided the secondary circuit into two parts, and separated their inner ends by a small condenser j^3 made of paraffined paper and tinfoil sheets. The outer ends of the secondary circuit were connected to the sensitive

tube or coherer, T, and the inner ends of its two sections were connected through two choking coils to the relay or local telegraphic instrument (see Fig. 6). The reason for this construction is that the outer ends of the secondary circuit are potential antinodes or loops, and by joining in the local or relay circuit in the centre of the secondary circuit, as shown, less interference is produced in the amplitude of the potential variation at the tube terminals than if the relay circuit was connected to these terminals, as previously the case.

In this specification Marconi gave details of the windings of two "jiggers" suitable for working with sending and receiving aerials 140 feet high, the transmitting system being the simple aerial directly connected to one secondary spark ball of an induction coil as already described.

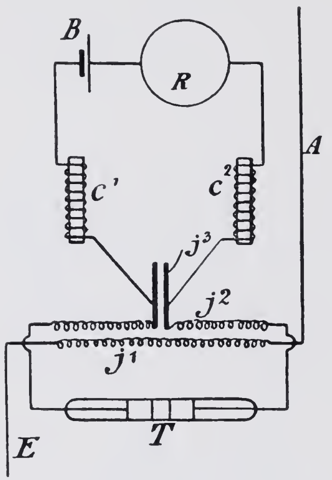


Fig. 6.—Arrangement of Apparatus in Marconi Receiver for Electric Wave Telegraphy. A, antenna; E, earth wire; T, sensitive tube, or cymoscope; j^1, j^2, circuits of jigger; j^3, condenser in centre of jigger secondary; c^1, c^2, choking coils; R, relay; B, relay battery.

"The specification for these transformers is as follows: The following are the details of the coil shown in Fig. 7. The primary is wound on a core 0·6 cm. in diameter, and consists of 100 turns of copper wire 0·037 cm. (No. 28 S.W.G.) in diameter, insulated with single silk covering and coated with paraffin wax. The secondary is of copper wire 0·019 cm. (No. 36 S.W.G.) in diameter, insulated with single silk covering, and is wound over the primary, commencing in the middle and in the same sense as the primary. Each half of the secondary is in layers of the following number of turns: first layer, 77; second, 49; third, 46; fourth, 43; fifth, 40; sixth, 37; seventh, 34; eighth, 31; ninth, 28; tenth, 25; eleventh, 22; twelfth, 19; thirteenth, 16; fourteenth, 13; fifteenth, 10; sixteenth, 7; seventeenth, 3; making 500 in all."

The following are the details of another coil described in the same patent specification:—

"The primary wound on a core 2·5 cms. in diameter consists of 50 turns of copper wire 0·07 cm. (No. 22 S.W.G.) in diameter, insulated with single silk covering. The secondary is of copper wire 0·005 cm. (No. 47 S.W.G.) in diameter, insulated by a single silk covering, and is wound over and in the same sense as the primary. Each half of the secondary consists of 160 turns in a single layer."

The inventor points out that the best results are obtained when the secondary circuit of the oscillation transformer has a total length equal to that of the transmitting aerial. This, however, must be understood to apply to the form of simple transmitting aerial up to that time used. We shall consider more particularly in another chapter the general physical theory of these oscillation transformers.

A large variety of forms of receiving oscillation transformer have at various times been employed by Marconi, and it forms a very important element in his system. In order to secure good results, or, in fact, any result at all, the length of the secondary circuit of this

receiving oscillation transformer must bear a certain relation to the length of the wave used.

The types of oscillation transformer the details of which are given above were found to be suitable for working with a wave length of about 600 or 700 feet, corresponding to an aerial 140 feet in height, when the transmitting arrangements were as already described. If the oscillation transformer, or *jigger*, is not wound to suit the wave length employed, so far from being a benefit, it prevents any signals being received at all.

The employment of a properly designed oscillation transformer in the receiving aerial was, however, found by Marconi to increase very considerably the range of working of the apparatus when using the receiving arrangement comprising the metallic filings tube as already described. Hence, towards the end of 1898 he was able to attempt wireless telegraphy over still greater distances than he had been able previously to accomplish.

4. Marconi's English Channel Experiments in 1899.—Just before Easter, 1899, Marconi obtained from the French Government permission to erect a mast for wireless telegraph experiments at

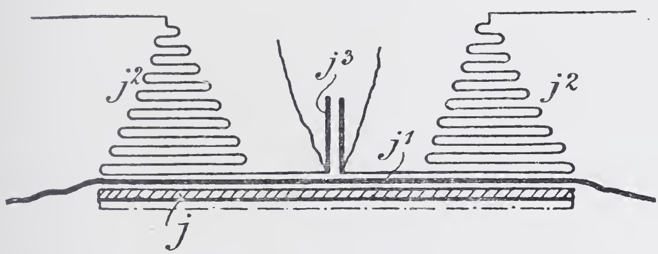


FIG. 7.—Half-section of Jigger, as used in Receiver shown in Fig. 6. j^1, jigger primary circuit; j^2, jigger secondary circuit; j^3, jigger condenser.

Wimereux, near Boulogne, in France, and a corresponding mast was erected at the South Foreland Lighthouse, near Dover, on the coast of England. The distance of these stations from one another was 32 miles (50 kilometres).

The apparatus for sending and receiving was erected in a small room in the South Foreland Lighthouse on the English side of the Channel, and on the French side in the Chalet d'Artois, at Wimereux (see Fig. 8).

The aerial wires were single-stranded copper wires 150 feet long, insulated with indiarubber, and upheld at the top by ebonite rods as insulators. As soon as the plant was complete Marconi transmitted messages, on March 27, 1899, across the English Channel, and sent communications in this manner from Wimereux to numerous scientific friends in England. The result was to create an immense public interest in the achievement all over the world. Up to that moment wireless telegraphy by electric waves had attracted only a very limited general attention; but the bridging of the English Channel by electric waves was one of those sensational feats which at once aroused the daily press to lively comment on the matter. The author, after spending some time in examining the appliances and working, wrote

a letter to the *Times*, published on April 3, 1899, part of which was as follows :—

"During the last few days I have been permitted to make a close examination of the apparatus and methods being employed by Signor Marconi in his remarkable telegraphic experiments between South Foreland and Boulogne, and at the South Foreland Lighthouse have been allowed by the inventor to make experiments

By kind permission of the Marconi Wireless Telegraph Company, Ltd.

FIG. 8.—Mast and Antenna Wire at the Chalet d'Artois, Wimereux, Boulogne, whence the first wireless messages were sent across the English Channel in March, 1899, by Mr. Marconi.

and transmit messages from the station there established both to France and to the lightship on the Goodwin Sands, which is equipped for sending and receiving ether wave signals. Throughout the period of my visit, messages, signals, congratulations, and jokes were freely exchanged between the operators sitting on either side of the Channel, and automatically printed down in telegraphic code signals on the ordinary paper slip at the rate of twelve to eighteen words a minute. Not once was there the slightest difficulty or delay in obtaining an instant reply to a signal sent. No familiarity with the subject removes the feeling of vague

wonder with which one sees a telegraphic instrument merely connected with a length of 150 feet of copper wire run up the side of a flagstaff begin to draw its message out of space and print down in dot and dash on the paper tape the intelligence ferried across 30 miles of water by the mysterious ether.

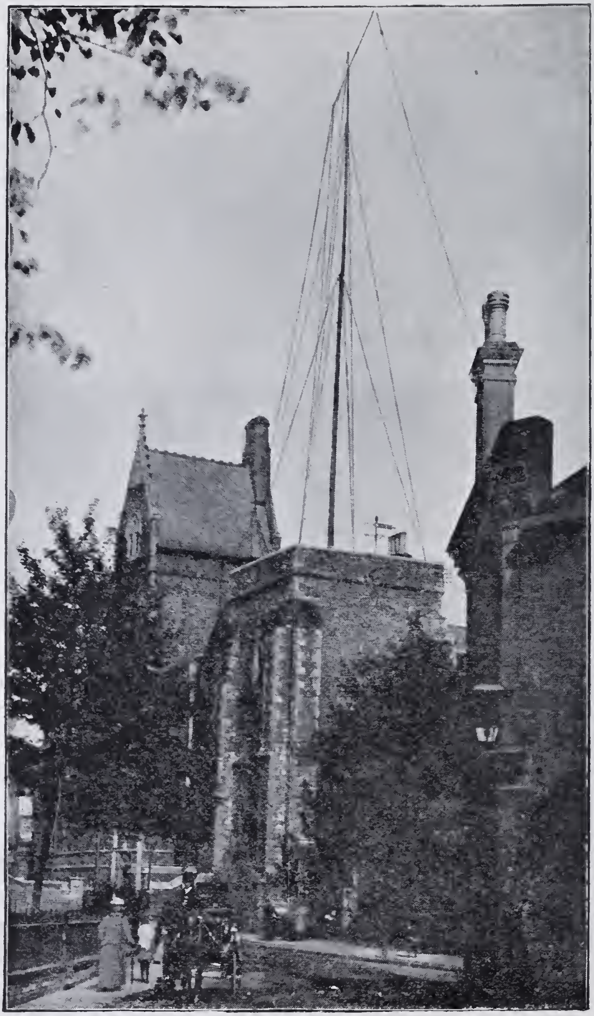
"The apparatus, moreover, is ridiculously simple and not costly. With the exception of the flagstaff and 150 feet of vertical wire at each end, he can place on a small kitchen table the appliances, costing not more than £100 in all, for communicating across 30 or even 100 miles of channel. With the same simple means he has placed a lightship on the Goodwins in instant communication, day and night, with the South Foreland Lighthouse. A touch on a key on board the lightship suffices to ring an electric bell in the room at South Foreland, 12 miles away, with the same ease and certainty with which one can summon the servant to one's bedroom at an hotel. An attendant now sleeps hard by the instruments at South Foreland. If at any moment he is awakened by the bell rung from the lightship, he is able to ring up in return the Ramsgate lifeboat, and, if need be, direct it to the spot where its services are required, within a few seconds of the arrival of the call for help. In the presence of the enormous practical importance of this feat alone, and of the certainty with which communication can now be established between ship and shore without costly cable or wire, the scientific criticisms which have been launched by other inventors against Signor Marconi's methods have failed altogether in their appreciation of the practical significance of the results he has brought about.

"Up to the present time none of the other systems of wireless telegraphy employing electric or magnetic agencies has been able to accomplish the same results over equal distances. Without denying that much remains yet to be attained, or that the same may not be effected in other ways, it is impossible for any one to witness the South Foreland and Boulogne experiments without coming to the conclusion that neither captious criticism nor official lethargy should stand in the way of additional opportunities being afforded for a further extension of practical experiments. Wireless telegraphy will not take the place of telegraphy with wires. Each has a special field of operations of its own, but the public have a right to ask that the fullest advantage shall be taken of that particular service which ether wave telegraphy can now render in promoting the greater safety of those at sea, and that, in view of our enormous maritime interests, this country shall not permit itself to be outraced by others in the peaceful contest to apply the outcome of scientific investigations and discoveries in every possible direction to the service of those who are obliged to face the perils of the sea. If scientific research has forged a fresh weapon with which in turn to fight nature, 'red in tooth and claw,' all other questions fade into insignificance in comparison with the inquiry how we can take the utmost advantage of this addition to our resources."

Although many scientific men at that time refused to admit that these cross-Channel experiments were indications of the utility of the Marconi telegraphy, some of the remarks in the author's letter to the *Times* just quoted received singular confirmation a few days later. During a dense fog on the Channel on April 28, 1899, a steamer, the *R. F. Matthews*, outward bound, ran into the East Goodwin Lightship and inflicted serious damage. The lightship, however, being provided with the Marconi apparatus, was able to communicate at once with the station at South Foreland Lighthouse, and tugs and a lifeboat were sent out immediately from Ramsgate to the assistance of the lightship. But for this timely aid the lightship would most probably have sunk. These demonstrations were continued uninterruptedly during the year 1899.

In the autumn of that year the British Association held its annual assembly at Dover. This meeting, taking place just a hundred years after the date of Volta's epoch-making invention of the Voltaic pile, was made the occasion of certain celebrations. The author, by request, delivered an evening discourse on "The Centenary of the

Electric Current" before the British Association in the Town Hall, Dover. At his suggestion a mast had been erected on the tower for the purposes of wireless telegraphy (see Fig. 9). The Marconi apparatus was set up on the lecture table and placed in direct

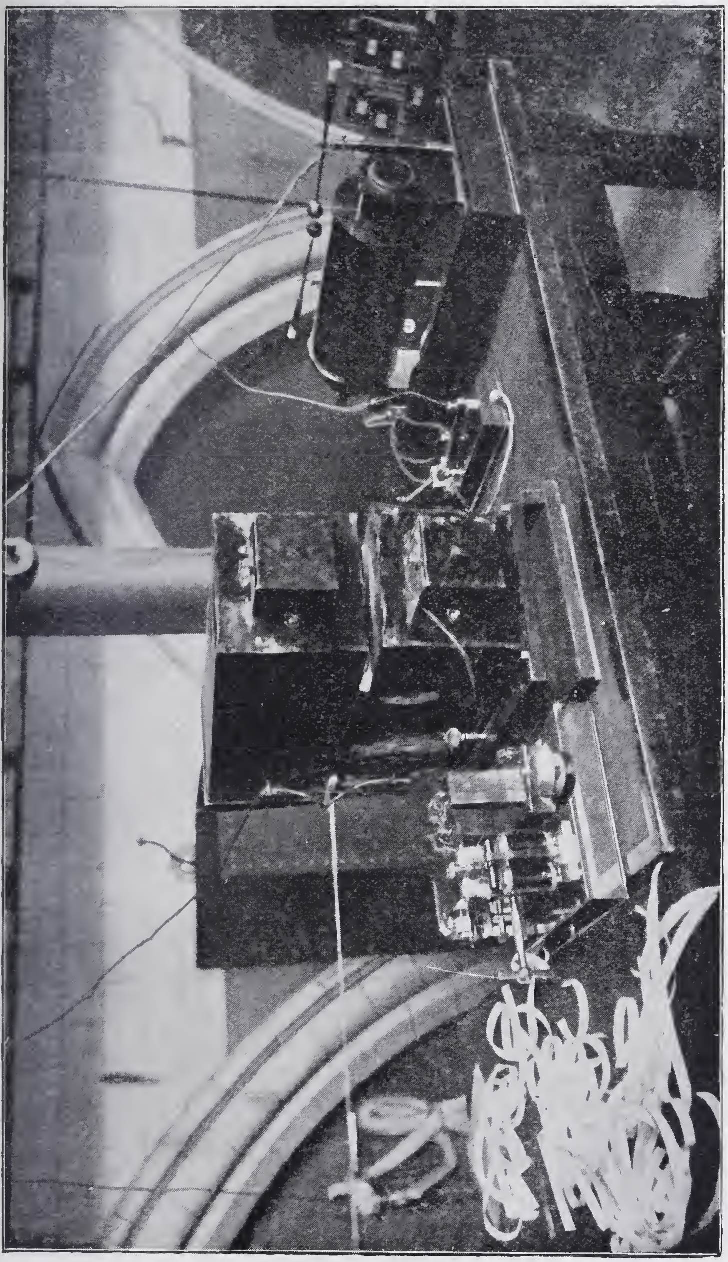


From "The Electrician."

Fig. 9.—Mast and Marconi Aerial Wire erected on the Tower of Town Hall, Dover, August, 1899, for Reception of Messages from France during the Meeting of the British Association in September.

communication with the South Foreland Lighthouse (4 miles), with Wimereux, in France (33 miles), and with the East Goodwin Lightship (12 miles) (see Fig. 10).

During the lecture messages were sent to the President of the



From "The Electrician."

FIG. 10.—Marconi Wireless Telegraph Apparatus arranged on the Lecture Table in the Town Hall, Dover, for a Lecture by Dr. J. A. Fleming, F.R.S., on "The Centenary of the Electric Current," before the British Association, September, 1899.

French Association for the Advancement of Science (M. Brouardel), then meeting at Boulogne, and numerous messages exchanged with the South Foreland station and the East Goodwin Lightship. Subsequently messages were sent from Wimereux, in France, and received directly at a Marconi station established at Chelmsford, in England, a distance of 85 miles, of which 30 miles were over sea and 55 miles over land. The height of aerials at both stations was 150 feet.

In the same year, the interest of the public being greatly aroused over the races for the International Cup between British and American yachts, Mr. Marconi went over to the United States and employed his apparatus and system of telegraphy between a ship and the shore, for reporting the results of the races during their progress, for the *New York Herald* newspaper. Over four thousand words were transmitted in less than a total of five hours' work done on different days.

A more important application was, however, made in July and August, 1899, during the naval manœuvres of the British Navy. Three vessels of the Reserve Squadron were fitted with the apparatus, and most important evolutions were carried out by orders given by Marconi wireless telegraphy. Two cruisers (*Juno* and *Europa*) were equipped, and in some cases important orders and information were transmitted instantly 85 miles. A full account of the result obtained was published by Commander S. Statham, R.N.[13] In this work the value of the oscillation transformer in the receiving aerial was fully demonstrated, and also the fact that the curvature of the earth seemed in no way to interfere with the transmission of the electromagnetic waves radiated from the aerials even over great distances. These demonstrations assisted to establish electric wave wireless telegraphy both for naval and mercantile marine purposes on a firm basis.

Contracts with large transatlantic shipping companies, and agreements with the Corporation of Lloyd's for establishing coast stations, and regular and permanent services of wireless communication between ship and ship and ship and shore, were soon after made by Marconi's Wireless Telegraph Company, Limited.[14]

By the end of 1900 the new supermarine wireless telegraphy had taken an unassailable position as an essential aid to navigation, commerce, and naval operations.

5. Marconi's Work on Syntonic Wireless Telegraphy, 1899–1901.—From the very commencement of practical electric wave telegraphy it was recognized that some means must be found for limiting the receptivity of wireless telegraph stations. The simple form of wave-detecting arrangement, first used by Marconi before he introduced the peculiar oscillation transformer just described, is sensitive to electric waves varying very considerably in wave length; in fact, a single electromagnetic impulse, or so-called solitary wave, if

[13] See article in the *Army and Navy Illustrated*, August, 1900; also a Friday Evening Discourse at the Royal Institution by G. Marconi, February 2, 1900, *Proc. Roy. Inst.*, vol. xvi. No. 94, p. 251.

[14] The Wireless Telegraph and Signal Company, Limited, was registered on July 20, 1897, with a capital of £100,000, to work the Marconi system of wireless telegraphy and manufacture the Marconi apparatus. In 1900 the name was changed to that of Marconi's Wireless Telegraph Company, Limited.

strong enough, will affect it. Hence atmospheric electrical discharges and stray or vagrant waves sent out by any source are picked up by it.

Several distinct problems here present themselves. In the first place, we may desire to make any given receiving station normally responsive only to electromagnetic waves of one particular wave length. In the next place, we may wish to render that station proof against deliberate attempts to hinder communication by throwing on to it violent vagrant or disturbing waves. Thirdly, we may want to prevent foreign stations from picking up messages not intended for them which are being sent out from some transmitter, and intended only for some particular receiving station.

The first problem is an easier one to solve than the second and third. We shall defer to a later section the consideration of the different practical solutions which have been offered of these problems, and confine ourselves here to a brief description of Marconi's work in 1900 on this subject. All the methods he has so far adopted are based upon the principle of resonance or syntony, and upon the fact that oscillations of different frequency can coexist in circuits which have a common part.

Early in 1900 Marconi applied for a British patent (No. 7777 of April 26, 1900), in which appliances were described for conducting syntonic telegraphy as well as simultaneous multiplex telegraphy with single aerials.

Some mention of these advances was made by the author in a letter published in the *Times* of October 4, 1900, in which the results of certain remarkable demonstrations given in the previous month were described. Reference was also made to them in Cantor lectures on "Electric Oscillations and Electric Waves," given by the author to the Society of Arts in November and December, 1900; and they were subsequently more fully discussed in a paper read to the Society of Arts by Mr. Marconi on May 15, 1901, entitled "Syntonic Wireless Telegraphy." [15]

The particulars of the apparatus described in the above-mentioned specification of Marconi are as follows:—

At the transmitting end the original arrangement of an aerial wire connected to one spark ball of the induction coil, the other being earthed (now called a plain aerial), was exchanged for an aerial consisting of a pair of inductively coupled circuits. A condenser, usually taking the form of a battery of Leyden jars, had one terminal connected to one spark ball of an induction coil, and the other to the primary circuit of an oscillation transformer. The opposite terminal of this transformer circuit was joined to the second spark ball. These spark balls were placed, as usual, in connection with the secondary terminals of an induction coil. The secondary circuit of this oscillation transformer was inserted between the aerial wire and the earth plate, and an adjustable inductance coil included in the circuit (see Fig. 11).

The oscillation transformer is constructed as follows: It consists of a square wooden frame, wound over with a number of lengths of highly insulated, thick-stranded copper cable joined in parallel, so as

[15] See *Journal of the Society of Arts*, issue for May 17, 1901, vol. 49, p. 505.

to make a primary circuit of one turn of extremely low resistance. In some cases two or more turns may be employed. Over this is wound a secondary circuit of 5 to 10 turns, and the oscillation transformer is usually immersed in a vessel of highly insulating oil. This secondary circuit is joined in between the aerial and the earth, a variable inductance being interposed. When in position the oscillation transformer forms an inductive coupling between two circuits—one a nearly closed oscillation circuit of large capacity and small inductance, and the other an open oscillation of much smaller capacity and greater inductance.

These circuits are more or less closely "coupled" by varying the distance between the primary and secondary. By the adjustment

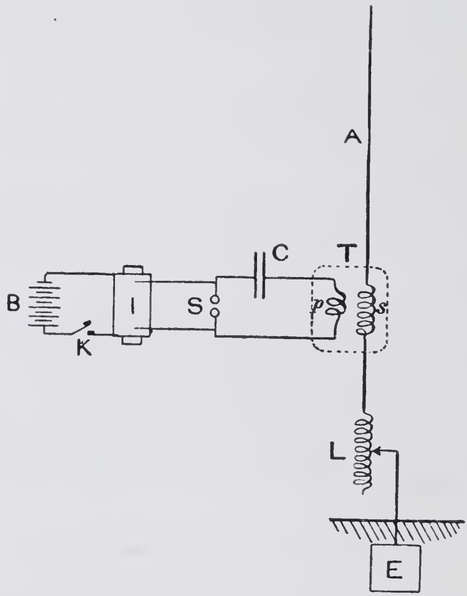


Fig. 11.—Arrangement of Transmitting Apparatus in Marconi System of Syntonic Wireless Telegraphy. A, antenna; L, tuning inductance; E, earth plate; *p*, *s*, oscillation transformer; C, condenser; S, spark balls; I, induction coil; B, battery; K, sending key.

of the variable inductance inserted between the earth plate and the secondary circuit of the oscillation transformer, and by variation of the capacity of the condenser in the primary circuit, the two circuits are brought into resonance with each other. When oscillations are set up in the closed circuit by the discharge of the condenser, the energy stored up in the Leyden jars is gradually drawn off and radiated by the open circuit. The closed circuit thus forms a reservoir of energy, and it is in itself a slightly damped circuit or persistent oscillator. The open circuit is a good radiator, and is kept supplied with energy by the reservoir. Hence we have a much more persistent train of oscillations set up in the aerial at each discharge than would be the case if the only storage of energy were that due to the

small capacity of the aerial. The important matter, however, is the proper "tuning" of the two coupled circuits. This can be effected in several ways:—

One plan is to employ a hot-wire voltmeter which is connected to two points on the circuit of the earth wire leading from the secondary circuit of the oscillation transformer to the earth plate. When oscillations are set up in the aerial, there is a difference of potential between these points, and the needle of the hot-wire voltmeter makes a more or less steady deflection. This reading depends not only upon the maximum value of the oscillatory current during each train of oscillations, but upon the logarithmic decrement, and upon the number of groups of oscillations which take place per second. If the spark gap remains the same length, and the number of spark discharges per second is kept constant, then any change in the capacity of the condenser in the primary circuit or in the inductance of the aerial circuit will make this voltmeter reading either greater or less. We then make some small change in one of these factors, say the condenser capacity, such that the voltmeter reading is slightly increased. We then continue in the same direction until the voltmeter reading begins to decrease again. In this manner we can tell approximately when we have given such value to the capacity that the current in the aerial is a maximum for a given spark length and spark frequency. This indicates that the two coupled oscillation circuits are approximately in syntony. Another method is to alter the inductance in series with the aerial and secondary circuit of the oscillation transformer until the maximum potential difference between terminals of this secondary circuit is reached, as evidenced by the spark discharge between them being of the greatest possible length.

For the purposes of this test, a sliding ball discharger, highly insulated, with means for easily altering the distance of the balls, is joined across the secondary terminals of the transformer.

A third method is to hold a rectangle of wire near the lower part of the aerial, the rectangle having inserted in it a vacuum tube, preferably one containing rarefied neon.[16] If the rectangle is placed with one side parallel to and near the aerial, the oscillatory currents induced in it will cause the vacuum tube to glow. We now alter either the inductance or capacity in either of the circuits, and notice whether the tube glows at a greater or less distance from the aerial, and so proceed to make small changes until we have succeeded in making the tube glow at the greatest possible distance from the aerial. This indicates that we have produced the maximum oscillation of current in the aerial. The spark length and spark frequency must, of course, remain unchanged during the test.[17]

Turning next to the receiver, the diagram of connections of Marconi's syntonic receiver is shown in Fig. 12.

A is the aerial wire, which may or may not be terminated in a plate

[16] The advantages of using rarefied neon in a vacuum tube as a means of detecting electrical oscillations were first pointed out by the author in a paper read to the British Association in 1904. See *Phil. Mag.*, October, 1904, p. 419.

[17] Another and more effective means is to employ the author's cymometer to make a measurement of the oscillation constant of the open and closed circuit respectively, and then to adjust the circuits so that they have the same oscillation constant. See Chap. VI. § 16.

or cylinder, *f*. At the foot of this aerial is an adjustable inductance, *g*, and this is connected to an earth plate, E, through the primary circuit, j^1, of an oscillation transformer. The terminals of this transformer are connected by a small sliding condenser, *h*. The secondary circuit, j^2, of this transformer is cut in the middle, and a condenser, j^3, inserted. The outer terminals of the secondary circuit are connected through two small variable inductances, g^1 and g^2, with the terminals of the sensitive tube, T, and are also connected by an adjustable condenser, *h'*. From the terminals of the middle condenser, j^3, proceed

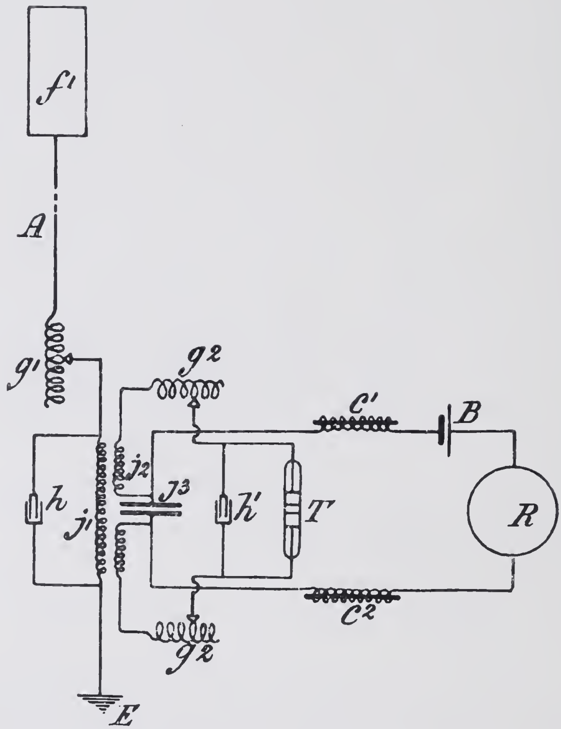


FIG. 12.—Arrangement of Receiving Apparatus in Marconi System of Syntonic Wireless Telegraphy. A, antenna; E, earth plate; g^1, g^2, tuning inductance; j^1, j^2, jigger; j^3, jigger condenser; c^1, c^2, choking coils; T, sensitive tube, or coherer; R, relay; B, battery.

two wires, which pass through choking coils, C^1 and C^2, and include the relay, R, and local cell, B, for working the relay. The Morse inker or other telegraphic instrument and associated battery connected to the relay are omitted from the diagram. The oscillation transformer, or jigger, placed in this receiving arrangement has its secondary circuit wound as already described in Marconi's three British Specifications, No. 12,326 of 1898, and Nos. 6982 and 25,186 of 1899 (see § 3 of this chapter).

To syntonize the receiver with itself and with the transmitter, the

two circuits, viz. the open circuit, comprising the receiving aerial, and the closed circuit, comprising the secondary circuit of the oscillation transformer, and the inductances g^1 and g^2, and the condensers j^3 and h' in series with it, must be adjusted so that this open and closed circuit are in resonance with each other, and have the same natural time period as the transmitter circuits intended to correspond with them. These different frequencies are technically termed the various *tunes*, and the operation of putting the circuits into syntony or resonance is called *tuning* the receiver and transmitter to themselves and to each other.

In his British Patent Specification, No. 7777 of 1900, Marconi gives the details for nine *tunes*. For example, one tune he calls No. 7, and he gives the particulars of the transmitter and receiver as follows :—

The transmitting aerial consists of four vertical stranded 7/22 copper wires, each 48·6 ms. long, connected together at the top or insulated end, but kept apart throughout their length by being suspended from the arms of a wooden cross, each arm of which is 4 ms. long.

The capacity in the primary of the oscillation circuit consists of a number of Leyden jars in parallel, having a total capacity of 0·016 mfd.

The oscillation transformer consists of a square wooden frame, the side of which is 30·48 cms., or 12 inches, in length, wound over with a primary circuit of one turn, the total length of the primary being 150 cms. The secondary circuit consists of six turns of insulated wire wound on the same frame, three turns on each side of the primary. These two circuits are made of highly insulated indiarubber-covered stranded copper cable, and the transformer, when made, is immersed in a vessel of highly insulating oil.

The oscillation transformer in the receiver has a secondary circuit consisting of 73·15 ms. of single silk-covered copper wire, No. 40 S.W.G., wound in one layer on a glass tube 5 cms. in diameter. The secondary is divided at its middle point. There are two primary circuits, each consisting of 2·75 ms. of copper wire 0·7 mm. in diameter, wound on tubes 6·5 cms. in diameter. The two primaries are placed over the two sections of the secondary circuit, and are joined in parallel. Another tune he calls No. 8, and gives particulars as follows :—

The transmitting aerial consists of a single stranded 7/22 copper wire 48 ms. long.

The condenser in the primary circuit of the transmitter consists of one or more Leyden jars having a total capacity of 0·007 mfd. The oscillation transformer in the transmitter has a primary circuit consisting of ten insulated wires, each 1·5 ms. in length, wound once round a square frame, the size of which is 30 cms., the ten wires being joined in parallel. The secondary circuit consists of 48·64 ms. of insulated wire, wound over the primary in 16 layers, the first or inner layer having nine turns, the second eight turns, the remainder seven, six, five, and two turns respectively.

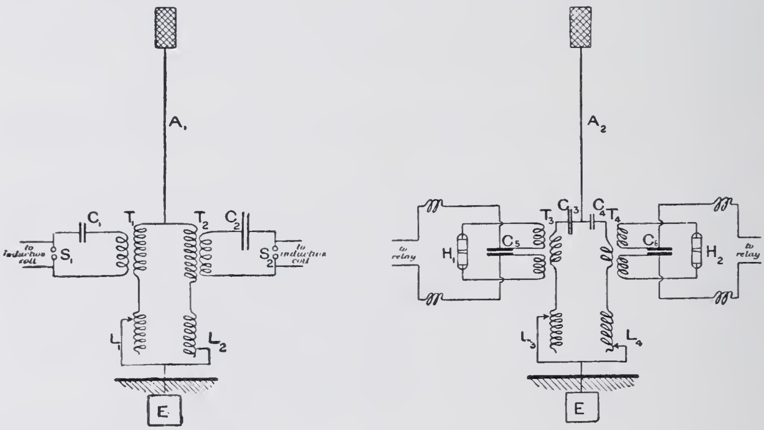
The oscillation transformer in the corresponding receiver has a secondary circuit consisting of 48·64 ms. of single silk-covered copper

wire 0·37 mm. in diameter, wound on a tube 9·6 cms. in diameter in one layer and cut at its middle point, to insert the condenser. The primary is 3·64 ms. long, made of wire 0·7 mm. in diameter, wound symmetrically over the middle portion of the secondary circuit in one layer.

In both cases the receiving aerial is identical with the transmitting aerial. Marconi states that these two tunes give good signals over distances of 190 miles.

The invention of the above-described apparatus enabled Marconi, in the summer of 1900, to conduct and exhibit duplex wireless telegraphy by sending and receiving simultaneous messages from one and the same aerial.

The arrangements at the sending and receiving ends were as shown in Fig. 13. At the transmitting end the two transmitters are



Transmitting station. *Receiving station.*

Fig. 13.—Arrangement of Transmitting and Receiving Apparatus in Marconi System of Multiple Syntonic Wireless Telegraphy.

connected to the same aerial wire, and each transmitter is operated independently by its own key. Two sets of waves are, therefore, radiated from the aerial, one which we may call the A wave, and the other the B wave.

At the receiving end two receiving sets are also connected, as shown to one and the same aerial, and when the adjustments are properly made, one of these receivers responds only to the A wave, and the other only to the B wave. Hence the transmitters may be set to work simultaneously, and simultaneous but different messages received on the two transmitters.

6. Transatlantic Wireless Telegraphy.—Marconi's investigations on syntonic telegraphy were essential steps in the accomplishment of his great ambition, viz. long-distance transoceanic wireless telegraphy.

In January, 1901, he established wireless communication on his system between St. Catherine's, in the Isle of Wight, and the Lizard,

in Cornwall, a distance of 200 miles. This was first done on January 23, 1901, the first day of the reign of His Majesty King Edward VII.

The facts were mentioned soon after in an address given by the author to the Liverpool Chamber of Commerce on February 12, 1901, on the application of wireless telegraphy to communication with lightships and lighthouses.[18]

Previously to this, however, in June, 1900, when Mr. Marconi returned from the United States, after having achieved the feat of sending wireless messages over 100 miles, he had arrived at the decision to make a serious attempt to send an electric wave across the Atlantic and detect it on the other side. He had long held in view the application of his system of wireless telegraphy to transatlantic working, not merely as an experimental feat, but with the object of making it a means for commercial communication.

It was obvious, however, that if such a purpose was to be brought to fruition it would necessitate the employment of more powerful electromagnetic waves than those previously used, and it was, above all things, necessary to be perfectly certain that the production of these waves would not prevent or cripple the already established wireless communication between ships and the shore. Moreover, the nature of the plant to be employed required careful consideration.

Up to that date the only appliances used in creating the waves had been ordinary induction coils taking, say, 200 or 300 watts, and giving a 10- or 20-inch spark. At most, therefore, half a horse-power had been the expenditure in electrical wave making. The condensers used had been ordinary Leyden jars, and no difficulty had been found in making and breaking the 15- or 20-ampere primary current of the induction coil, with a heavy Morse key to make the signals. Although Marconi had long since shown that increase in the height of the aerial increased the effective range of signalling, the practicable height of masts for supporting the aerial was considered to be about 200 feet. Hence the conclusion was that transatlantic wireless telegraphy could only be accomplished by the employment of greater electrical wave energy. This, however, necessitated substituting for apparatus of a physical laboratory character, viz. induction coils, Leyden jars, etc., engineering plant much more powerful, yet arranged so as to be safe to use.

Knowing the experience which had been gained by the Author in dealing with extra high-tension alternating currents in electric-lighting work, Mr. Marconi invited his assistance in July, 1900, in specifying the nature of the electrical engineering plant to be used, and also in designing special portions of the apparatus for generating and controlling the powerful electromagnetic waves it was desired to create and use. This involved many experiments on a small scale before embarking on the construction of large and costly plant of an entirely new type.

A convenient site at Poldhu, near Mullion, on the coast of Cornwall, was leased in August, 1900, for the erection of the first electric wave power station, and the construction of appropriate buildings

[18] See *Liverpool Courier* and *Liverpool Journal of Commerce* of February 13, 1901.

was commenced in October, 1900, by the Marconi Wireless Telegraph Company.

In the interests of scientific history, it may be well just to mention briefly the facts and dates connected with the first serious attempt at transatlantic wireless telegraphy. The machinery specified by the Author, after consultation with Mr. Marconi, began to be erected at Poldhu in November, 1900, and Mr. Marconi at the same time decided the nature of the aerial that he proposed to employ. This was to

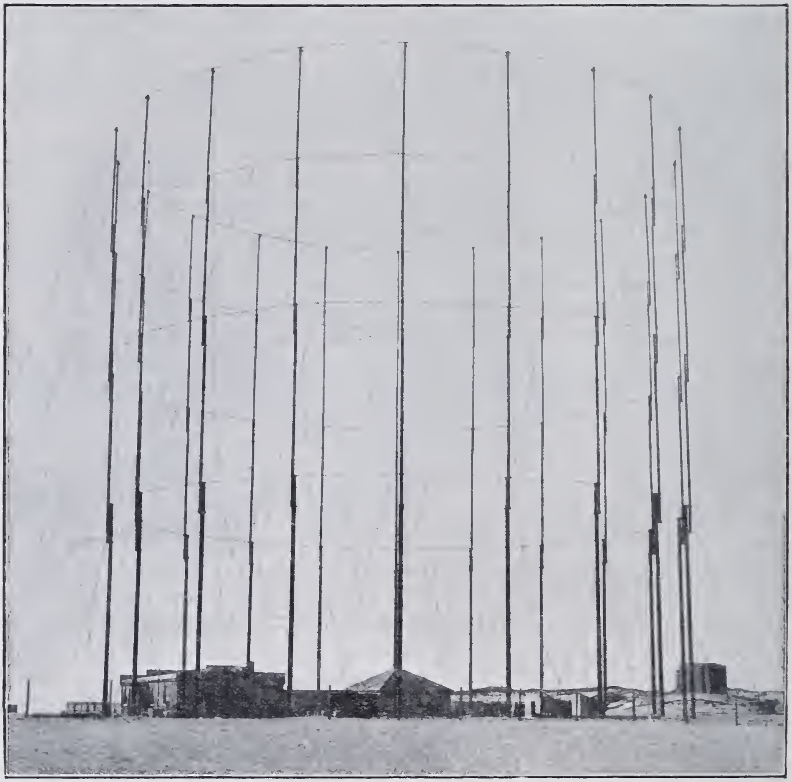


Fig. 14.—Circle of Masts, 200 feet in height, originally erected to sustain the Conical Antenna at the Poldhu and Cape Cod Electric Wave Power Stations in 1901, for Marconi's Transatlantic Wireless Telegraphy.

consist of a ring of 20 masts, each 200 feet high, arranged in a circle 200 feet in diameter, the group of masts supporting a conical arrangement of wires insulated at the top and gathered together at the lower point in the shape of a funnel (see Fig. 14).

In December, 1900, the building work was so far advanced that the writer was able to send down drawings showing the arrangement proposed for the electric plant in the station. This being delivered and erected, experiments were tried by the Author at Poldhu in

January, 1901, for the purpose of ascertaining how far it would be efficient for the purpose in view.

At Easter, 1901, the Author paid a second long visit to the Poldhu station, and, by means of a short temporary aerial, conducted experiments between Poldhu and the Lizard, a distance of 6 miles, which were sufficient to show that the work was being conducted on the right lines.

A view is given in Fig. 15 of the Poldhu station—the first electric wave power station in the world—at this stage of the enterprise.

During the next four months much work was done by Mr. Marconi and the Author together, in modifying and perfecting the wave

From a photograph by the Author.

Fig. 15.—Photograph of the First Buildings erected in 1900 at Poldhu, Cornwall, England, for Experiments on Transatlantic Wireless Telegraphy.

generating arrangements, and numerous telegraphic tests were conducted during the period by Mr. Marconi between Poldhu, in Cornwall, and Crookhaven, in the south of Ireland, and Niton, in the Isle of Wight. A delay occurred owing to a storm on September 18, 1901, wrecking a number of the masts; but sufficient restoration of the aerial was made by the end of November, 1901, to enable Mr. Marconi to contemplate making an experiment across the Atlantic. He left England on November 27, 1901, in ss. *Sardinian*, for Newfoundland, taking with him two assistants—Messrs. Kemp and Paget—and also a number of balloons and kites. He arrived at St. John's, in Newfoundland, about December 5, and made arrangements for sending up a balloon and an attached aerial wire. Having previously instructed his assistants at Poldhu, he cabled on December 9, 1901, to begin a programme consisting in sending the letter "S" (which, on

the Morse alphabet, consists of three successive dots) from 3 p.m. to 6 p.m. each day. Signals began to be sent out in this manner from Poldhu, in Cornwall, on Wednesday, December 11; and after some difficulty in elevating the aerial wire in Newfoundland by means of a kite, Marconi received the "S" signals at St. John's, in Newfoundland, on Thursday, December 12, 1901. On Friday, December 13, he confirmed this result, and on Saturday, December 14, 1901, he was able to cable a message to Major Flood Page, one of the directors of the Marconi Wireless Telegraph Company in London, to this effect:—

"St. John's, Newfoundland, Saturday, December 14, 1901. Signals are being received. Weather makes continuous tests very difficult. One balloon carried away yesterday."

In these experiments the actual power employed in Cornwall for the production of the waves was not more than 10 or 12 kilowatts. The sending aerial consisted of fifty bare stranded copper wires, 7/20 in size, suspended from a triatic stay, strained between two masts 160 feet in height and 200 feet apart. The wires were arranged in a fan shape, and connected together at the bottom by a bar, a common wire being brought from the junction through the roof of the station. With this arrangement, however, electromagnetic waves were produced, which crossed the Atlantic and retained sufficient energy at a distance of 2200 miles to influence the receivers employed by Mr. Marconi.

Full details of his operations on arriving in Newfoundland were given in a communication published in the *Times* of January 3, 1902. On arriving in Newfoundland, Mr. Marconi secured the goodwill and assistance of the Governor, Sir Cavendish Boyle, and also of the Premier, Sir Robert Bond, who offered him every assistance. They placed at his disposal a room in a disused Government building, which occupied a site on a Signal Hill—a lofty eminence overlooking the port of St. John's, Newfoundland (see Fig. 16). This hill is crowned by a plateau, 2 acres in extent, and afforded an ample area for manipulating the kites and balloons. On this site the receiving apparatus was set up, and on Monday, December 9, 1901, Mr. Marconi and his assistants began their work. By Wednesday they had inflated their balloon, and it made its first ascent, carrying with it the aerial wire; but it soon broke away and was lost. On Thursday they succeeded in elevating a kite to a height of 400 feet, which kept an aerial wire attached to it elevated in space.

As the object of these experiments was in the first place to ascertain whether an electric wave generated with any such power as 10 to 25 kilowatts could be made to traverse the Atlantic, and follow round the curvature of the earth, it was obviously out of the question to make the costly permanent arrangements requisite for utilizing the best forms of syntonic receiver.

The aerial wire used consisted of a copper wire 400 feet long, upheld by the kite, which, in the strong wind then prevailing in Newfoundland, was rising and falling irregularly during the experiments. Hence the electrical capacity of the wire was varying, and it was impossible to make use of any form of syntonic apparatus. Marconi was therefore obliged to use the next best means at his disposal.

He hardly expected to obtain in this first attempt, especially with non-syntonic apparatus, oscillations in his temporary receiving aerial sufficiently strong to actuate one of his ordinary receivers, including a nickel filings tube, tapper, and relay, neither was it absolutely necessary to record the signals. He therefore employed a telephone as a receiver, simply connected in series with a coherer of some kind. Those employed consisted of tubes containing loose carbon powder and cobalt filings, and also the form of carbon mercury-iron self-restoring cymoscope already described under the name of the

By permission of the Century Company, New York.

FIG. 16.—Government Building on Signal Hill, St. John's, Newfoundland, in which Mr. Marconi received the First Electric Wave Wireless Telegraphic Signals sent across the Atlantic from Poldhu Power Station in December, 1901.

"Italian Navy coherer." Experience had shown that a tube of the latter kind, although not well adapted for syntonic telegraphy, yet when used in series with a source of small continuous electromotive force, such as a shunted Leclanché cell, and a telephone, was extremely sensitive.[19] On the second day experiments were made to

[19] Assertions were subsequently made that Marconi had achieved the feat of detecting electric waves across the Atlantic by the aid of other inventions than his own. As the object of these first experiments was to discover if the waves could be detected at all, he naturally made use of the most appropriate means known to him. The use of a telephone as a means of detecting small but sudden changes in the resistance of a microphonic or imperfect contact was already well known, and there was no reason why he should not have employed it if convenient.

In a discourse delivered subsequently at the Royal Institution, June 13, 1902,

ascertain if intelligible messages could be sent, but the difficulties of maintaining the temporary aerial elevated by a kite at the precise times, when the waves, by preconcerted arrangement, were being sent, rendered the few signals so received indistinct.

Nevertheless, it had been demonstrated that an electric wave generated by no inordinate power could traverse the Atlantic and retain sufficient energy at that distance to affect a telegraphic wave-detecting device. This achievement created an immense sensation in every part of the civilized world.

These profoundly interesting experiments were, however, brought to an untimely end by the action of the Anglo-American Telegraph Company, who had a monopoly of receiving in Newfoundland trans-atlantic messages until April 15, 1904. They entered a peremptory demand for these experiments to cease, and although this was generally regarded as a tactical mistake on their part, Mr. Marconi complied and removed his apparatus.[20]

The experiments, however brief, demonstrated to Mr. Marconi, his colleagues, and co-directors, that if permanent aerials and appropriate power stations were erected on the coasts of Great Britain and the United States, electric wave wireless telegraphy between them was fully practicable.

7. **Long-distance Wireless Telegraphy, 1902–1907.**—Returning to England in February, 1902, Marconi made arrangements for the erection at Poldhu of a permanent structure for carrying a large aerial. This consisted of four wooden lattice towers, each 210 feet high, placed at the corners of a square 200 feet inside. These structures were designed and erected under the superintendence of Mr. A. E. Heming, one of the Marconi Company's engineers. They were strongly stayed by wire ropes, and surrounded by stairways for ascending to the top (see Fig. 17 and *Frontispiece*). The towers carried insulated rope triatic stays, from which was suspended a conical arrangement of four hundred copper wires forming the aerial, put up in sections so that more or less could be employed. The buildings for the generating plant were placed in the middle of the area. Additional machinery was obtained, and improvements carried out which had been indicated by experience.

At the same time similar towers and stations were erected at Cape Cod in Massachusetts, U.S.A., and at Cape Breton in Nova Scotia.

Mr. Marconi devoted himself with immense energy and perseverance to the work of further improving the sending and receiving apparatus. In much of the work the author was confidentially consulted and assisted in specifying the plant and devising new appliances for creating and controlling the electric oscillations generated. In February, 1902, Marconi returned to Canada, and on the way across the Atlantic conducted interesting experiments on

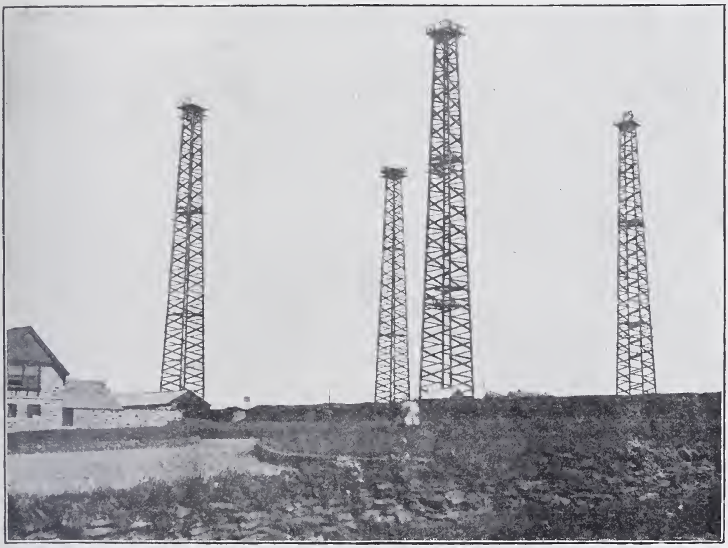
"On the Progress of Space Telegraphy," Mr. Marconi described in detail the methods he had employed, and made acknowledgment of the assistance he had received from all those who had aided him in the design and working of the appliances employed. See *The Electrician*, 1902, vol. 49, p. 392; and also the *Proceedings of the Royal Institution*, 1902, vol. xvii. p. 208.

[20] See the *Times* of January 3, 1902, and contemporary newspapers for details of this controversy and incident.

board the American liner the ss. *Philadelphia*. An insulated aerial wire 60 metres high was fixed to the ship's masts. Messages sent from Poldhu were received on board as the vessel went west and printed down on the Morse tape. Readable messages were obtained in this way up to 1551 miles from Cornwall, and indications or signals up to 2099 miles, by the aid of the Marconi receivers already described.

A fact of considerable interest observed on this voyage was that the signals could be received at a greater distance by night than by day. They ceased entirely at 700 miles distance by day, but were detectable up to 1551 miles by night. We shall make further reference to the probable reason for this difference in Chap. IX.

In July, 1902, Marconi conducted similar experiments on board



From a photograph by the Author.

FIG. 17.—Lattice Towers erected at Poldhu, Cornwall, England, to carry the Antenna Wires for the Marconi Electric Wave Power Station.

the Italian warship *Carlo Alberto*, generously placed at his disposal for this purpose by the Italian Government, on a voyage from England to Cronstadt, and on this occasion he employed his magnetic detector as a receiving instrument (see Chap. VI. p. 449), the invention of which had occupied him for some long time previously.

On July 7, 1902, the *Carlo Alberto* left Dover for the Baltic, having been equipped with an arrangement of aerial wires and with receiving apparatus. Messages were received on board from Poldhu as far as Cape Skagen, in Denmark (800 or 900 miles), and (July 15) at Cronstadt (1500 miles).

In these experiments a considerable part of the great circle line between the sender and receiver lay over land.

In August, 1902, the *Carlo Alberto* proceeded to the Mediterranean,

continuing to receive wireless messages from Poldhu on the way.

On September 11, 1902, the managing director of the Marconi Wireless Telegraph Company, was able to announce in a letter to the *Times*, that the *Carlo Alberto*, which left England on August 23, had reached Spezia (Italy), and had been in constant communication, by electric wave telegraphy, with Poldhu during the voyage. Perfect messages were received in Gibraltar Harbour and throughout the Mediterranean voyage. Telegrams for the King of Italy and the Italian Minister of Marine were received from Poldhu and printed on Morse tape in Spezia Harbour. A glance at the map shows that the electric waves in this case must have crossed the Bay of Biscay, Spain, France, and the Alps. Subsequently the *Carlo Alberto* was placed at the disposal of Mr. Marconi by the Italian Minister of Marine for the purpose of additional tests across the Atlantic.

The *Carlo Alberto* sailed from Plymouth with this object on October 20, 1902, for Sidney, Nova Scotia. She was fitted especially for this voyage with gaffs, by which antenna wires could be elevated 25 metres above the trucks of the spars forming her normal rig (see Figs. 18 and 19). Between these spars on the main and fore masts was slung an insulated stay, from which 50 copper wires, forming the aerial, were suspended. The operating room was built round the after conning tower. Messages were received from Poldhu during the voyage and whilst the ship was lying in Sidney Harbour.

Towards the end of 1902 the structures erected at the Nova Scotia and Cape Cod stations to carry the great aerials were sufficiently advanced to enable preliminary tests to be undertaken. On December 21, 1902, Marconi was able to send the following message to England from Glace Bay, Nova Scotia :—

"I beg to inform you that I have established wireless telegraphic communication between Cape Breton, Canada, and Poldhu, in Cornwall, England, with complete success. Inauguratory messages, including one from the Governor-General of Canada to King Edward VII., have already been transmitted (December 21) and forwarded to the Kings of England and Italy."

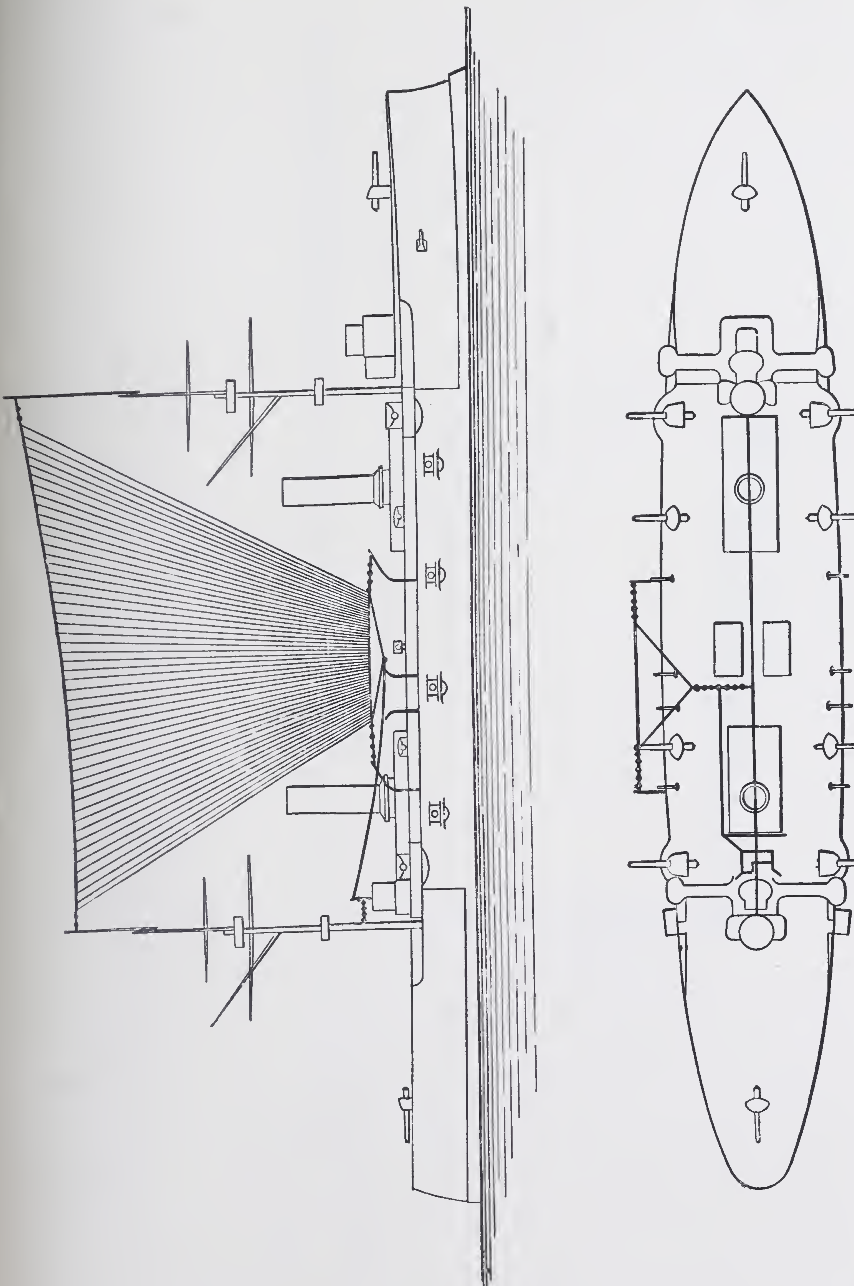
Following this announcement came the news that on January 19, 1903, a wireless message was transmitted across the Atlantic from Wellfleet, Cape Cod, Massachusetts, U.S.A., to Poldhu, Cornwall, England, from Mr. Roosevelt, President of the United States, to King Edward VII., as follows :—

"To His Majesty King Edward VII., London.

"In taking advantage of the wonderful triumph of scientific research and ingenuity which has been achieved in perfecting the system of wireless telegraphy, I extend on behalf of the American people the most cordial greetings and good wishes to you and all the people of the British Empire."

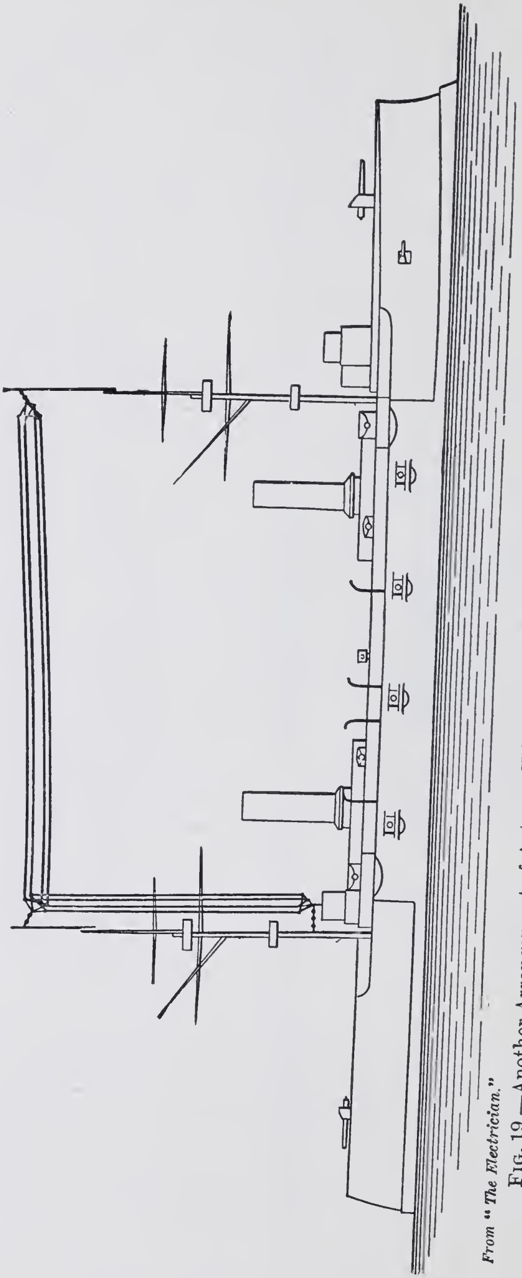
The electromagnetic waves conveying this message travelled 3000 miles over the Atlantic, following round an arc of 45° on a great circle, and were detected telephonically by the Marconi magnetic receiver at Poldhu.

In the next few months a large number of messages were sent in this manner in both directions across the Atlantic. In April some news messages were transmitted to the *Times*, but the service was



From "The Electrician."

FIG. 18.—View of the Italian Battleship *Carlo Alberto*, showing the Arrangement of Antenna Wires used during Mr. Marconi's Voyages in the Baltic and Mediterranean Seas.



From "The Electrician."

FIG. 19.—Another Arrangement of Antenna Wires employed on the *Carlo Alberto* for Wireless Telegraphic Work on Mr. Marconi's Voyages.

interrupted by breakdown of a portion of the transmitting appliances in the stations on the American side. It is not necessary to devote space to discussing the causes of these delays in the fulfilment of the expectations which had been raised as to the speedy establishment of regular wireless telegraphy across the Atlantic.

The history of transatlantic wireless telegraphy has so far followed very much on the lines of the history of submarine cable Atlantic telegraphy. It will be remembered that the first attempt to lay a cable across the Atlantic in August, 1857, was a failure. In 1858 a cable was laid successfully, but it broke down after a life of three months, when about 700 messages had passed through it. From that date there was an interval of nearly seven years before means and resolution were forthcoming to make a fresh attempt. A third effort was made in 1865, but it was only in 1866, or nine years after the first expedition, that a cable was laid which established uninterrupted commericial communication.[21]

Hence, although those interested in the submarine cable industry have not been slow to announce their belief that wireless transoceanic telegraphy can never be brought to a condition to compete with cables from a commercial point of view, impartial students of the history of electrical technology will hesitate before endorsing this opinion.

We have only to glance backwards at the early history of submarine cable telegraphy itself, electric telephony, or electric lighting, to see that when there is a substantial scientific achievement on which to work, technical skill and commercial enterprise have a foundation on which a superstructure of commercial success may be subsequently erected, even although preliminary failures and great initial difficulties have to be faced. The facts which were established beyond question by the end of 1902 were, that telegraphic messages could be sent 3000 miles across the Atlantic by electromagnetic waves, at a speed and with a certainty which is not in any degree inferior to that effected by ordinary submarine cable telegraphy, when employing single transmission and hand sending.

This was done in little more than six years from the date of Marconi's first public exhibition of electric wave wireless telegraphy in Great Britain, conducted over a maximum distance of only *two* miles. In view of this fact, he will be a bold prophet who will venture to affirm what may not be done in six years more.

It is useless, however, to expend time in speculating whether transoceanic wireless telegraphy is destined to affect the traffic through cables. The history of past competitions of an analogous kind shows that they will probably coexist. When the news came to England in 1878 that Edison had succeeded in making a practical incandescent electric lamp, a serious fall in gas shares occurred. The public jumped to the conclusion that the new electric light would kill gas. It took fifteen years for the use of the incandescent lamp to make any impression at all on private gas lighting; and subsequent improvements in gas burners have resulted in more gas being used now than before the advent of electric lighting.

The public in the same manner flung their cable shares on the

[21] See "The Story of the Atlantic Cable," by Mr. Charles Bright. Newnes & Co. London, 1903.

market in the spring of 1902, in the belief that the wireless telegraphy would immediately replace the present submarine cable telegraphy, and sensational newspaper announcements assisted the depression.

On the other hand, experience shows that it is unwise to prophesy failure for any technical enterprise which has a real basis of scientific fact beneath it. It has been demonstrated that ordinary code and commercial messages can be transmitted across the Atlantic by electromagnetic waves, but outstanding questions of speed, cost, certainty, and privacy must await decision by the resistless arbitrament of facts and events. There is no question, however, that long-distance electromagnetic wave telegraphy has come to stay, and will not only stay, but continue to advance.

One important matter, however, was completely settled in 1903, viz. that the power-station working could be conducted without any interference with the ship-to-shore or ship-to-ship wireless telegraphy. Statements having been made in some technical journals to the effect that the establishment of power stations for the production of electromagnetic radiation suitable for long-distance telegraphy would render it impossible to conduct the highly necessary ship-to shore communication, the author had the opportunity afforded to him by Mr. Marconi, in March, 1903, of putting this contention to crucial test.

There is at Poldhu a mast and aerial removed by 100 yards or so from the aerial of the power station. Six miles away, at the Lizard, there is a Marconi station in connection with Lloyd's, for communication with vessels proceeding up and down the Channel which are equipped with Marconi apparatus. It was arranged that at a certain time wireless messages should be sent off simultaneously from the power station and from an ordinary ship equipment in connection with the isolated mast at Poldhu, and received on two Marconi receivers connected to the aerial at the Lizard. These experiments took place on March 18, 1903, under the direction of the author, and different written messages were handed in to the sending operators at the power station and neighbouring small or ship station, the operators not knowing a moment before the message that would be given to them. Some of these messages were in cypher and some of a commercial character. For example, the following cypher message was despatched in Morse code from the power station:—

"Bulfish, London. Streamlet Solstice Turtle. Worthily, John Brown, Captain."

Simultaneously the following was despatched from the small station 100 yards away, viz.:—

"A thick fog prevails here. SS. *Mignonette* has been run down by a foreign ship. Send tugs immediately."

At the Lizard station all these messages were received by Mr. Marconi and printed on Morse slip, pair and pair simultaneously on two independent Marconi receivers attached to the same aerial. In no case was any mistake made. To be sure that the power station was sending out waves much more powerful than those of the small station, other receivers were placed at Poole, 200 miles away, and the

messages from the power station alone were recorded there. These were telegraphed back for verification by postal telegraph immediately on arrival.

The author described these results and exhibited the messages as sent and as received a few days afterwards at a Cantor lecture at the Society of Arts.[22]

The tests were confirmed some months later by Admiralty officials. Mr. Marconi went to Gibraltar on board the British battleship *Duncan*, then under command of Captain (now Admiral Sir) H. B. Jackson, and during the voyage similar experiments were undertaken. During the stay of the *Duncan* at Gibraltar wireless messages were received from Poldhu, including one official communication. The tests were watched on board H.M.S. *Duncan* by Admiral Jackson, and at the Poldhu station by Lieutenant F. G. Loring, R.N. It was definitely ascertained that the short-distance Marconi apparatus supplied to the Admiralty for ordinary naval use was not affected by the action of the electromagnetic waves sent out from the power station at Poldhu.

These proofs and experiences enabled Mr. Marconi shortly afterwards to establish a regular system of news transmission from Poldhu to Atlantic liners *en voyage*.

Small newspapers are now published on board the Atlantic liners daily which contain news paragraphs received during the previous night from the power station on the mainland. The inauguration of this enterprise took place on the Cunard liner *Campania* in June, 1904, when Mr. Marconi kept the vessel during the entire voyage in receipt of communications either from Poldhu, in Cornwall, England, or the station at Cape Breton, in Nova Scotia, or that at Cape Cod, near Boston, U.S.A. The longest distance covered by a message on that occasion was one sent from Poldhu, received on board the *Campania* when 2250 miles from England. It was a message of thirty words relating to the submersion test of an American submarine boat. The daily paper published on board is entitled the *Cunard Daily Bulletin*. A representation of a page of it is shown in Fig. 20 (see p. 554).

By the end of 1909 the Marconi Wireless Telegraph Company had equipped more than 300 ships with the apparatus for wireless communication with each other and with coast stations. These included the principal passenger steamships of the Cunard, White Star, Norddeutscher Lloyd, Allan, American, Red Star, and Atlantic Transport and other British and Foreign Companies. Also vessels belonging to the Compagnie Transatlantique, Belgian Mail Packet, and Isle of Man Steam Packet Companies.

It has become an indispensable method for conducting naval signalling, and the use made of it in the Russo-Japanese war showed it to be a most important element in controlling naval tactics, so much so that the principal naval powers in the world were compelled to make it the subject of legislative control within the limits of their respective territorial authority.

During the siege of Port Arthur, the *Times* newspaper, with great

[22] See also a long letter from the author describing these tests, published in the *Times* for April 14, 1903.

enterprise, established ship and shore stations, and equipped them with apparatus for wireless telegraphy supplied by an American (The

CUNARD DAILY BULLETIN.

MARCONIGRAMS

DIRECT TO THE SHIP.

EDITORIAL OFFICE

R.M.S. "CAMPANIA."

Monday, June 6th, 1904, 1·00 p.m.

Received from the Marconi Station at Poldhu (England), 800 miles distant.

WAR NEWS.

According to a report from Admiral Togo Wireless Telegraph Stations have been erected on the promontory of Liau-ti-Shan.

—

Explosions occurred at Port Arthur on Saturday, from which it is inferred that new batteries are being prepared.

—

News has been received in Paris that the Russian Army Corps is executing a forced march southwards, having received urgent orders to re-occupy Liau-Tung Peninsula and relieve Port Arthur.

—

TIBET EXPEDITION.

The Tibet Expedition has captured two of the enemy's guns, and there is a report current that a Lhasa General has been killed.

—

AMERICAN NEWS.

A distillery at Peoria, Illinois, which is considered to be the second largest in the world, has been destroyed by explosions and fire, causing the death of ten persons.

STOP-PRESS.

—

WAR NEWS.
Russian Disaster.

Telegrams to hand state that Admiral Togo reports a further encounter, during which a Russian Gunboat was torpedoed and sunk in the vicinity of Port Arthur thus still further reducing the Russian fleet available in Eastern Waters.

Tuesday 2. a.m.

Communication was established and the following news received from Marconi Station, Cape Breton, (Canada), when the "Campania" was 2000 miles from New York.

ICEBERGS.

According to reports which continue to come to hand, more icebergs than usual have been sighted in the Atlantic, the steamer "Island" from Copenhagen for New York, in particular, reports having passed ten.

The Compagnie Generale Transatlantique "La Lorraine" reports icebergs in latitude forty forty-five to forty-two thirty longitude forty-eight twenty-seven to fifty fifty-four.

DEATH OF PRINCESS MARY OF HANOVER.

Telegrams to hand indicate that the death of Princess Mary of Hanover on Saturday last, has caused universal sorrow.

THE TIBET EXPEDITION.

Telegrams received confirm that the British have Captured two twenty-four pounders and killed a Lhasa General.

FINANCIAL NEWS.

Stocks dull generally and prices remain unchanged.

By kind permission of the Marconi Wireless Telegraph Company, Ltd.

FIG. 20.—Facsimile of a Page of the *Cunard Daily Bulletin*, published on board the Cunard Liners, containing Marconigrams sent by Wireless Telegraphy.

De Forest) Company. This proved to be a valuable means for securing early and authentic news from the seat of war.

It was the first, and probably will be the last, time that the

opportunity occurred for such an employment of wireless telegraphy.[23]

8. Marconi's Transatlantic Wireless Telegraphy.—Although the transmission of wireless messages between the station at Poldhu in Cornwall, England, and that at Cape Cod in Massachusetts, U.S.A., in 1902, had sufficiently proved the practicability of transatlantic radiotelegraphy, it was considered advisable by Mr. Marconi and his co-directors of the Marconi Wireless Telegraph Company to defer the attempt to conduct regular intercommunication until the completion of two new large radiotelegraphic stations, one placed at Glace Bay in Nova Scotia and the other at Clifden in Connemara, Ireland. These stations were sufficiently advanced by the middle of 1907 to admit of telegraphic work being inaugurated on October 17, 1907, and a limited service of press messages was undertaken. On February 3, 1908, the service was extended to ordinary messages between London and Montreal, the transatlantic rates proper being $2\frac{1}{2}d.$ for press and $5d.$ for ordinary messages. The evidence of the press using this Marconi wireless transatlantic service, such for instance as that of the *New York Times* and the London *Times*, was that its efficiency and promptness were in every way satisfactory.

Even then, however, the condition of permanent service had not been reached. A disastrous fire occurred in August, 1909, at the Nova Scotia station, and destroyed part of the plant, and it was not until the month of April, 1910, that the transatlantic wireless service for public use was again re-established.

How far such a supermarine wireless communication is capable of taking the place or even rivalling submarine cable communication for all purposes is not a question which can be decided by *à priori* arguments. Time alone will show. Nevertheless, the extraordinary rapidity with which this new method of intercommunication has been developed, and the relatively small capital outlay involved in it, make its progress a fact of the greatest importance in connection with the growing demands of the world for cheaper and more easily established methods of oversea intercommunication. Transatlantic wireless telegraphy by Hertzian waves is, however, now an accomplished fact, and in the only form in which it is yet practically available (1910) it is unquestionably the result of the indomitable perseverance and inventive ability of Mr. Marconi, aided by those whose faith in the possibilities of the enterprise have given him the necessary financial and technical support. Further details of the appliances used in these long distance stations are given in Chap. XI. on radiotelegraphic stations.

9. Supermarine Wireless Communication.—The complete establishment of radiotelegraphic communication between ships equipped with the necessary apparatus and shore stations enabled the Marconi Company to develop a form of oceanic wireless exchange between hundreds of vessels and the shore—such that no ship furnished with their apparatus was ever out of communication with its home ports. The enormous value of this system was on many

[23] Full details of the enterprise were given by Captain Lionel James, war correspondent for the *Times*, in a paper read to the Society of Arts, January 18, 1905.

occasions amply demonstrated. On January 23, 1909, the ss. *Republic*, a White Star liner, collided with the ss. *Florida* in the Atlantic, and in the absence of any means of securing help the passengers, crew and ship would in all probability have been lost. Fortunately, the ss. *Republic* had the Marconi wireless apparatus installed, and the operator, Mr. J. R. Binns, was able to establish communication with the Marconi shore station at Sias-conset, on Nantucket Island, and this station signalled the ss. *Baltic*, the ss. *La Lorraine*, and numerous other vessels, so that shortly seven vessels were on their way to give their aid. The captain of the *Baltic* was able to reach the injured vessel in time and rescue all those on board. A similar service was rendered in the case of the ss. *Slavonia* on June 10, 1909, which stranded on Flores Island, in the Azores. The signals brought the *Batavia*, 150 miles away, and the *Prinzessin Irene* to the aid of the *Slavonia*, and the 410 passengers and crew were taken off without the loss of a single life. The system, however, provides not merely a safeguard of unspeakable value in the case of accident, but the means by which messages can be transmitted from any British postal telegraph office to ships on the high seas within certain times and range. The exact time of sailing from port of the vessels fitted with the wireless apparatus being known, their position on the high seas with respect to certain shore radiotelegraphic stations at subsequent dates and times is also known, and can be ascertained from a communication chart issued by the Marconi Company. Messages can be sent to that vessel if within reach of any shore station or sent from other intermediate vessels if too far to be reached directly.

10. Contributions to Radiotelegraphy by Other Workers.—Whilst Marconi was thus successfully engaged in developing wireless telegraphy along lines which had removed it out of the region of unfruitful experiment into a condition of the greatest practical utility, other inventors began to make contributions to the subject which must be mentioned.

Sir Oliver Lodge, who had made the subject of electric oscillations and electromagnetic waves a special study, turned his attention in 1897 to the application of this knowledge to electric wave telegraphy, and later on associated himself with Dr. A. Muirhead, well known for his inventions in telegraphy, in developing radiotelegraphy.

In Germany, Prof. A. Slaby, of Charlottenburg, Count Arco, Prof. F. Braun, of Strasburg, Dr. J. Zenneck, of Brunswick, and many others began to cultivate the same field of research. Many other scientific workers, such as P. Drude, M. Abraham, M. Wien, E. Aschinass, G. Seibt, W. Schloemilch, and J. Dönitz, in Germany; Profs. Poincaré and Branly and MM. Blondel, Tissot, Ferrié, Ducretet and Turpain, in France; Prof. Righi and MM. Bellini and Tosi and Artom, in Italy; Prof. Popoff, in Russia; Mr. V. Poulsen, in Denmark; Profs. Trowbridge, G. W. Pierce, R. A. Fessenden, and Messrs. L. de Forest and J. J. Stone, in the United States, have made contributions of importance either to the theory or practice of radiotelegraphy.

In England, in addition to Mr. Marconi and his associates, including the author, Sir Oliver Lodge, Dr. Muirhead, Mr. Duddell,

and many others have contributed to the scientific or inventional side of the subject.

The officials of the British Postal Telegraph Service and British naval officers have carried on their own investigations on it.

In justice to English workers, it should be noticed that one of the earliest British patent applications for improvements in means for telegraphing or telephoning without wires was made by Mr. A. C. Brown and Mr. G. R. Neilson, who are both connected with the great submarine cable industry. These inventors filed their provisional specification, No. 28,955, on December 17, 1896, subsequently to the date of application of Marconi's first British patent, but previously to the filing of his corresponding complete specification. In this specification Brown and Neilson proposed to place a Hertzian wave oscillator in a box and project a beam of electric radiation into a receiver circuit at a distance which is to be "open or closed and preferably syntonized as nearly as possible to the generating circuit." One feature of interest in this specification is that they suggested the employment of a coherer containing "preferably, but not necessarily, carbon granules," used in series with a voltaic cell and telephone as an electric wave detector. They state that such a carbon coherer is self-restoring, or, at most, needs a few taps by hand at intervals to keep it in order.[24]

It is singular that the two patentees above named should have so nearly anticipated the type of detector afterwards used in conjunction with his aerial and earth connection by Marconi to read the first signals transmitted across the Atlantic. This patent specification of Brown and Neilson in many ways showed remarkable knowledge of the subject of Hertzian waves and their detection, but the patentees did not realize the fundamental importance of the antennæ and earth connections, as the absolutely essential appliances for electric wave wireless telegraphy.

We shall proceed to notice briefly some of these inventions, and to sketch out the chief contributions made by various workers to the evolution of electric wave telegraphy, and in later chapters discuss more in detail the modern appliances for conducting it and the working of radiotelegraphic stations.

11. The Work of Lodge and Muirhead.—Lodge's work on electromagnetic waves developed out of his investigations on electric oscillations and lightning discharges in connection with the protection of buildings from lightning.[25]

He discovered in 1889 that two metallic surfaces in imperfect but not conducting contact were welded together when an electric discharge passed between them,[26] and later on studied the propagation of electric waves along wires.[27] He thus came into close contact with the

[24] In view of the claims made subsequently by many other persons for priority in the use of the so-called telephonic method of reception, this specification of Brown and Neilson is worthy of notice.

[25] See "Lightning and Lightning Guards" (Whittaker & Co); also "On Lightning, Lightning Conductors, and Lightning Protectors," by Sir Oliver Lodge, *Journ. Inst. Elec. Eng.*, 1889, vol. 18, p. 386.

[26] See a paper on "Lightning Guards for Telegraphic Purposes," by Sir Oliver Lodge, *Journ. Inst. Elec. Eng.*, 1890, vol. 19, p. 352; also "The History of the Coherer Principle," *The Electrician*, November 12, 1897, vol. 40, p. 88.

[27] See Sir Oliver Lodge, "On the Theory of Lightning Conductors," *Phil. Mag.*, August, 1888, ser. v. vol. 26, p. 217, or *The Electrician*, August 10, 1888, vol. 21, p. 435.

researches of Hertz on the creation of electromagnetic waves in free space, and this work he both expounded and extended. Reference has already been made to his Royal Institution Lecture in 1894 on the "Work of Hertz and Some of his Successors."

His interest in these matters was, however, scientific rather than technical, and he himself has admitted that before the matter had received attention from others it had not occurred to him to suggest the employment of Hertzian waves for telegraphic purposes. In the course of his scientific work he had directed much attention to the phenomena of electric resonance. Hence, when once it had been indicated that the chief practical importance of Hertzian waves might lie in their application to space telegraphy, Lodge was not slow to apply to it his knowledge of this subject.

Before the date of Marconi's first patent application, Lodge had been occupied with the problem of space or wireless telegraphy by means of electromagnetic induction between two circuits at a distance, bringing to bear on it his acquaintance with the facts of syntony and resonance. As we are not concerned in this book with methods of space telegraphy other than that effected by true electromagnetic waves, we shall not enter into details of Lodge's work on magnetic inductive telegraphy in the field so long cultivated by Sir William Preece.[28]

At the beginning of 1897, owing to the announcements which had then appeared of the results obtained by Marconi, it became clear that electric wave telegraphy had unquestionable advantages over all previously tried methods, and scientific as well as public attention became concentrated on it.

On May 10, 1897, Lodge applied for a provisional patent protection in Great Britain (No. 11,575 of 1897) for "Improvements in Syntonized Telegraphy without Line Wires," and in this document he states that the object of this invention was to enable an operator to transmit messages across space to any one or more of a number of different individuals in various localities, each of whom is provided with a suitably arranged receiver. The subject-matter of the specification deals exclusively with the utilization of electromagnetic waves.

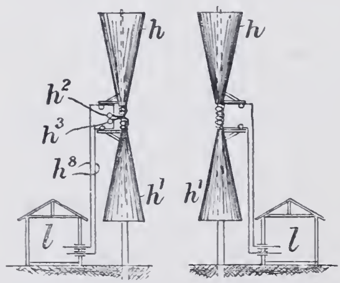


FIG. 21.—Lodge's Wing-shaped Antennæ for Electric Wave Telegraphy.

His radiator was described as consisting of a pair of "capacity areas," or triangular-shaped metal plates, h, h' (see Fig. 21), separated by a spark gap, but having an inductance coil, generally shown as a spiral of a few turns, interposed. In some cases this radiator was to be used horizontally, and in other cases vertically. In this last case the lower metal wing or area might be connected to the earth, or partly buried in the earth, and the upper wing extended by connection to an insulated plate.

[28] See a paper by Sir Oliver Lodge, "Improvements in Magnetic Space Telegraphy," *Journ. Inst. Elec. Eng.*, 1898, vol. 27, p. 799.

Lodge asserted that this form of radiator was capable of persistent or long-sustained oscillations, suitable, therefore, for effecting syntonic telegraphy. He was well aware, and states (*loc. cit.*, p. 2, line 53), that unless the radiator provides these sustained trains of waves, no true syntonic action is possible. A part of the specification is taken up with descriptions of methods of charging electrically these oscillators. The receiving arrangement was to consist of a pair of capacity areas (one of which might be the earth) similar to the transmitter, but containing in its circuit a Branly coherer, consisting of a tube of metallic filings with a "clock, or a tuning fork, or a cog wheel, or other device" mounted on the stand of the coherer to cause a tremor of sufficient intensity. This vibrator or decoherer was evidently to be maintained continuously in action. In some cases the coherer was inserted in the secondary circuit of "a species of transformer," the primary of which was in the circuit of the collecting wings, but no detailed instructions are given for making this oscillation transformer or properly relating the lengths of its circuit and its turns to the capacity and inductances of the collecting circuit. Without this adjustment the oscillation transformer is a detriment rather than an advantage.

Sir Oliver Lodge and Dr. A. Muirhead, the latter well known for his inventions in connection with submarine cable telegraphy, then joined themselves as co-patentees of other inventions in wireless telegraphy, and took out a British patent, No. 16,405 of July 10, 1897. This specification contains a description of numerous devices for causing the coherer or light metallic contact to be decohered by the current which passes through it from the local cell when the electric waves improve the contact. In one of these arrangements a siphon recorder is used as the telegraphic recorder, and the metallic contact is connected by a thread, p, with the recorder coil d, so that a movement of the coil jerks open the contact c (see Fig. 22). In another case the passage of the local current through the contact is made to impart a decohering jerk by the movement either of one of the cohering surfaces or else of a separate piece of metal attached to them, in a strong magnetic field. Broadly speaking, this specification covers devices for decohering a single point contact sensitive to electric waves. A third British specification by the same patentees, No. 18,644 of August 11, 1897, covers a variety of devices intended to give greater certainty of action. The inventors still adhere to the single-point coherer, but join two or more such contacts in parallel if necessary, applying to them vibrations created by clockworked cams or cylinders to keep

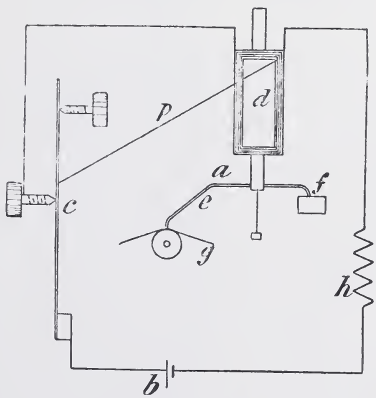


Fig. 22.—Lodge and Muirhead's Combination of Siphon Recorder and Point Coherer.

them in a sensitive condition. In fact, Lodge's method of using the coherer may be said to be, to keep it perpetually in a state of tremor or vibration, whereas the method adopted by Marconi is to apply a carefully regulated set of taps to decohere *after* the coherence has taken place. This specification of Lodge and Muirhead describes also a method of telegraphing by electric waves sent along a bare wire laid on the earth's surface.

A fourth British specification, No. 29,069 of December 8, 1897, by Lodge and Muirhead, is for "Improvements in Syntonic Telegraphy." The inventors introduce a large condenser, *a*, in series with the inductance coil *d* and capacity areas *b*, *c*, and join up the single- or multiple-point coherer, *e*, as a shunt across both inductances and condensers, whilst the local cell, *f*, and telegraphic instrument, *g*, viz. a Kelvin siphon recorder, is joined as a shunt across the condenser alone (see Fig. 23). In some cases they use the earth as one of the capacity areas. The same specification includes a description of an elaborate revolving commutator for changing the positions of the coherer and recording telegraphic instrument, so that each is in turn in the most favourable position in the oscillatory circuit. The author is not aware that any of these receivers or transmitters, with these wing-shaped capacity areas, have ever been employed in practical syntonic electric wave telegraphy.

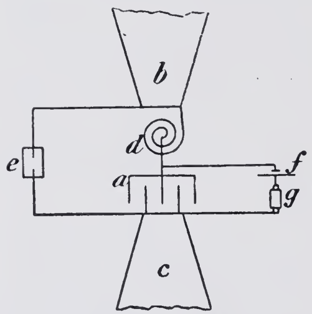
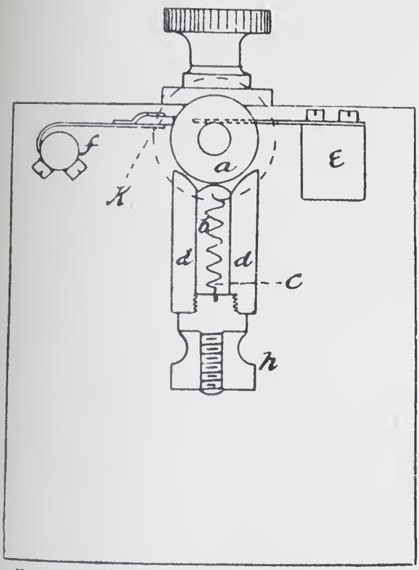


FIG. 23.—Lodge and Muirhead's Method of connecting the Coherer and Telegraphic Instrument to the Wing Antennæ.

Passing over an interval of time, we find that Lodge, Muirhead, and Robinson devised the self-restoring coherer, consisting of a rotating steel disc in contact with an oil-covered mercury surface, which has already been described (Chap. VI. § 6).[29] This coherer they employed to actuate directly a siphon recorder without the intervention of any relay, using a fraction of a volt (generally from 0·1 to 0·3 volt) obtained from a shunted voltaic cell as a working electromotive force. The device is arranged in a compact form, the steel disc lightly touching the oil-covered mercury surface, being revolved continuously by clockwork (see Fig. 24).

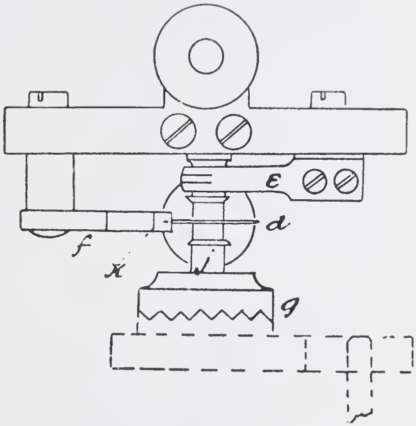
Lodge and Muirhead associated this self-restoring coherer with a receiving circuit and receiving aerial adjusted to have a definite time period of oscillation. For the transmitting arrangement they subsequently adopted a closed oscillation circuit consisting of a condenser, *l*, adjustable inductance, *m*, and spark ball discharger, *g*, in series, the condenser being charged by an induction coil, *c*, and discharging across the spark gap with oscillations. To this closed circuit an aerial wire, *f*, is directly coupled, and some other point on the closed oscillation circuit is connected to the earth, generally through a condenser, *n*, of large capacity. The arrangements of the

[29] See British Patent Specification, No. 13,521 of June 14, 1902, of Lodge, Muirhead, and Robinson.

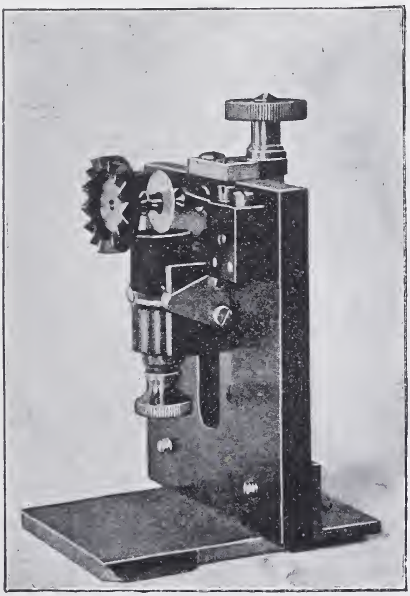


From "Page's Weekly Magazine."

(*Elevation.*)



(*Plan.*)



From "The Electrician."

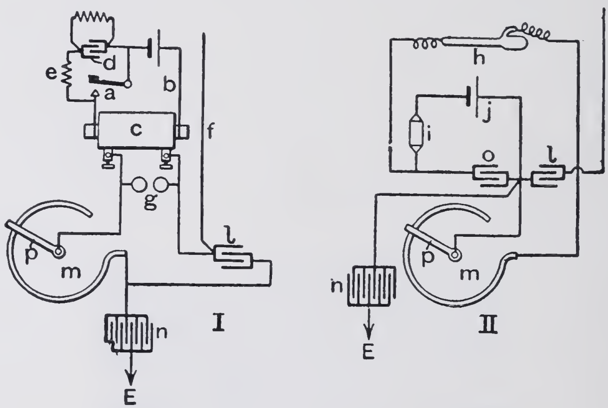
(*Perspective view.*)

FIG. 24.—Lodge-Muirhead-Robinson Mercury-steel Coherer. *a*, steel disc rotated by clockwork; *d*, mercury cup; *c*, mercury covered with oil; *e*, contact springs; *f*, wiper for cleaning edge of disc.

transmitter are as shown in the left-hand diagram in Fig. 25, taken from their British specification, No. 11,348 of June 3, 1901.

The length of the aerial or the inductance in the closed circuit has to be so adjusted that the aerial is in resonance with the closed circuit. This takes place when the aerial has such a length that its free time period of oscillation is that of the closed circuit, or is equal to an harmonic of the latter.[30]

The receiving circuit similarly consisted of an aerial, *f*, attached to some point on a closed oscillation circuit consisting of a condenser, *o*, and variable inductance, *m*, some other point on this last circuit being connected to the earth through a condenser, *n*. The coherer *h* is connected in series with the condenser and inductance in the closed circuit, as shown in the right-hand diagram in Fig. 25, taken from



Transmitter. *Receiver.*

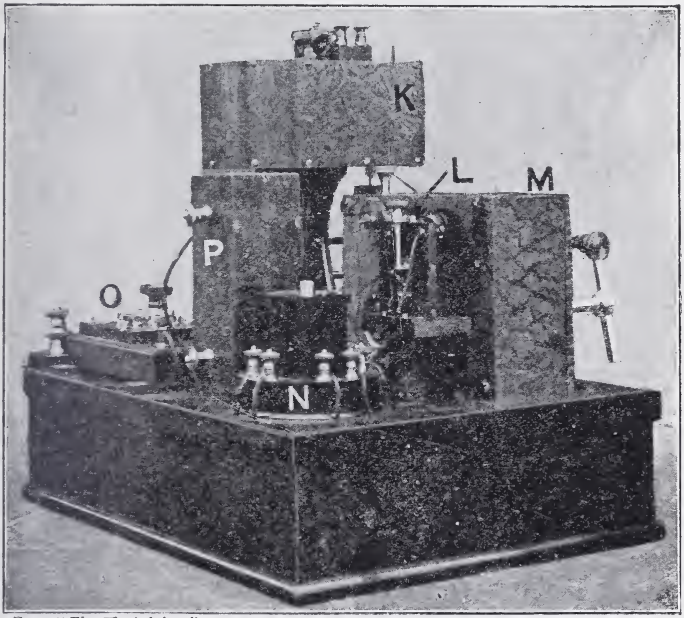
Fig. 25.—Diagram of Connections of Lodge-Muirhead Wireless Telegraph Transmitter and Receiver Apparatus.

the same British specification of Lodge and Muirhead, No. 13,521 of 1901.

The telegraphic recording instrument is a siphon recorder, and the local battery is a shunted cell which supplies an electromotive force of a fraction of a volt for working through the coherer. When the electromagnetic waves impinge on the aerial they set up oscillations which excite syntonic oscillations in the closed circuit associated with it, and these oscillations finally break down the insulation of the film of oil lying between the steel wheel and the mercury aided by the voltage of the local shunted cell. The siphon recorder in series with that cell then deflects and records a signal. If the train of arriving waves is short, then the record on the tape of the syphon recorder is a brief mark or triangular notch, corresponding to a *dot* on the Morse system. If the train of waves is more prolonged, then the mark on the tape is a square-shouldered notch, corresponding to a *dash* on the Morse code. In this manner the movement of the

[30] For a fuller discussion of the conditions of this resonance and the theory of such coupled circuits, see Chap. VIII. § 9 and § 10, of this treatise.

siphon recorder coil and associated pen imitates that of the key in the sending circuit. The siphon recorder, coherer, working cell, and shunt, or potentiometer, are combined in one piece of apparatus, as shown in Fig. 26. Instead of using a hand-manipulated Morse key at the sending end to create short or long trains of oscillatory sparks, and therefore waves, Dr. Muirhead employs an automatic sender, actuated by a perforated tape, as in the case of transmission by cable. The tape is perforated with the message in the usual manner by a hand-worked perforator, which punches the paper tape, as for the Wheatstone automatic transmitter, with the Morse symbols for each letter. The tape is then sent through a transmitter, which closes the circuit of a vibrating break or buzzer in the primary



From "The Electrician."

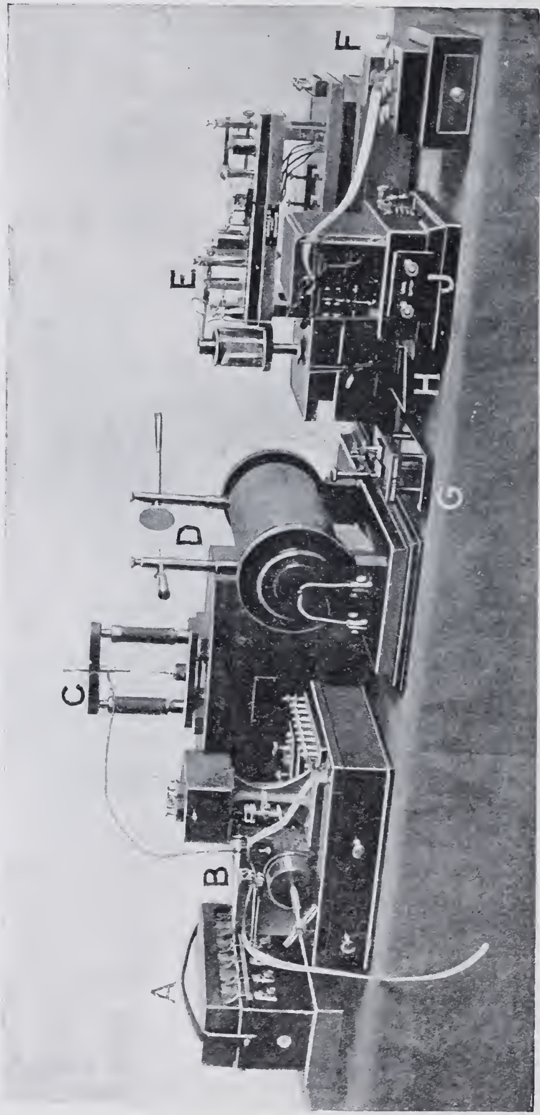
Fig. 26.—Lodge-Muirhead Combined Siphon Recorder, Coherer, Potentiometer, and Working Cell for their Wireless Telegraph Receiver.

circuit of the induction coil for a time, corresponding to the dash or dot on the Morse system. A view of the collected apparatus is shown in Figs. 27 and 27a.

The rotating steel disc cymoscope is said to work with great ease, regularity, and speed, and the advantages of dispensing with any form of sensitive relay are considerable. At the same time there is the advantage of a printed record of the message.

12. Work of Slaby and Von Arco on Wireless Telegraphy.—Dr. Adolf Slaby, one of the engineering professors in the Technical High School at Charlottenburg, Berlin, had his attention drawn to the utilization of Hertzian waves for telegraphic purposes prior to the date when Marconi's work became known, but, according to his

own statements, he obtained no practical results until the clue to success was given to him by witnessing, early in 1897, Marconi's



From "Page's Weekly Magazine."

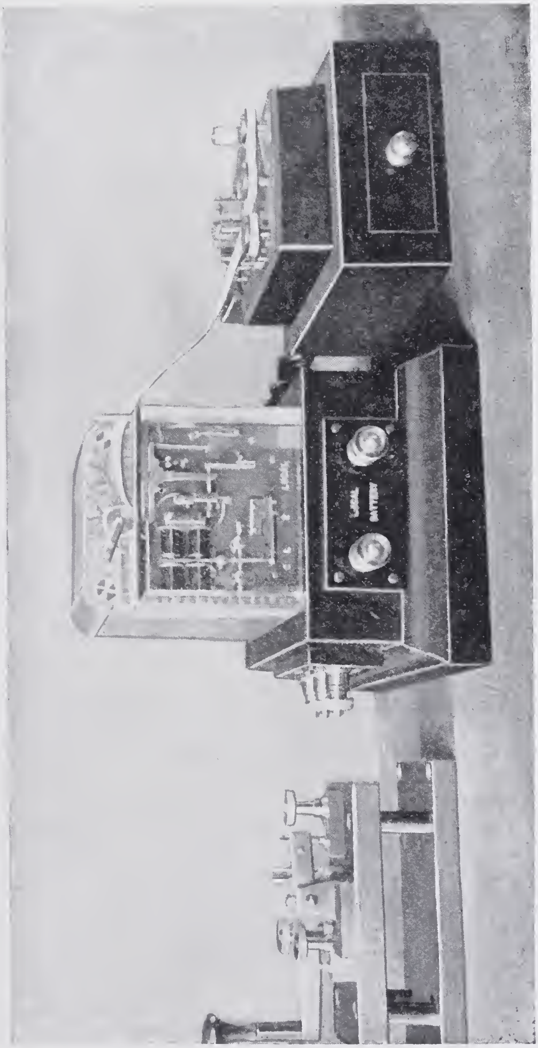
FIG. 27.—Lodge-Muirhead Apparatus for Electric Wave Wireless Telegraphy. A, 12-volt battery; B, combined siphon recorder and coherer; C, spark discharger; D, induction coil; E, buzzer or coil interrupter; F, tape perforator; G, Morse key; H, primary switch; J, autotransmitter.

demonstrations across the Bristol Channel.[31] From that time he has been a diligent worker in this field of research.

At the very outset he carefully studied the distribution of electric

[31] See an article on "The New Telegraphy," by Dr. A. Slaby, *The Century Magazine*, April, 1898, vol. 55, p. 870.

potential and current in the aerial wire as used originally by Marconi, and saw that stationary electric waves were set up in it, so that when vibrating electrically in the fundamental mode there was a node of potential at the base of the Marconi aerial and an antinode at the summit. This he saw applied not only to the transmitting aerial



From "Page's Weekly Magazine."

FIG. 27A.—Another View of the Signalling Key, Autotransmitter, and Perforator of Lodge-Muirhead Wireless Telegraphic Apparatus.

but to the receiving aerial. It then became clear, from the study he made of the Branly metallic filings tube, that this instrument depended for its operation on the application of a sudden and sufficient oscillatory electromotive force or potential difference between the ends of the tube. Hence the insertion of the tube

between the base of the aerial and the earth, as in the original Marconi arrangement, was using it under the least advantageous conditions.

Properly speaking, the tube should be inserted between the upper end of the aerial and the earth, so as to receive the maximum potential difference between its ends. This, however, is impossible without carrying up a second wire from the earth, which would then at once have a distribution of potential set up in it, similar to that in the aerial itself, and hence no difference of potential would exist between the ends of a coherer situated between the summits of the two equally tall aerials. Slaby, however, overcame the difficulty in a very ingenious manner. If we set up a vertical wire, AB (see Fig. 28), with its base connected to the earth in a region traversed by electric waves,

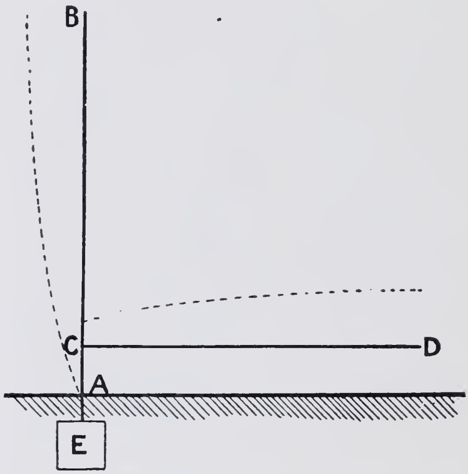


FIG. 28.—Slaby-Arco Antenna, AB, and Attached Syntonic Side Wire, CD. The distances of the dotted lines in the diagrams from the firm lines representing the antennæ denote the amplitude of the potential oscillations at the corresponding points.

we shall have stationary oscillations set up in it, when its length is adjusted to resonance with the time period of the impinging waves. If then we attach to a point two or three metres above the ground a horizontal wire, CD, of nearly equal length to the upper segment of the aerial (see Fig. 28), we shall have stationary oscillations of potential set up in both vertical and horizontal branches, as indicated by the ordinates of the dotted lines in Fig. 28. Hence there is a loop of potential at the outer end of the lateral wire as well as at the top of the vertical wire. We have easy access to the former point, and hence we can insert a coherer, F, between the outer end of the lateral wire and the earth E_1, placing in series with it a condenser, K, and shunting the condenser by a telegraphic relay, R, and local cell, G. The arrangement is shown in the diagram in Fig. 29, taken from the German patent, No. 130,723, of Slaby and Arco, applied for October 16, 1900. The claim made for the arrangement is that it enables

any vertical, earthed, but otherwise insulated, rod, such as a lightning conductor, to be employed as the aerial.

In a supplementary German patent, No. 131,585, applied for

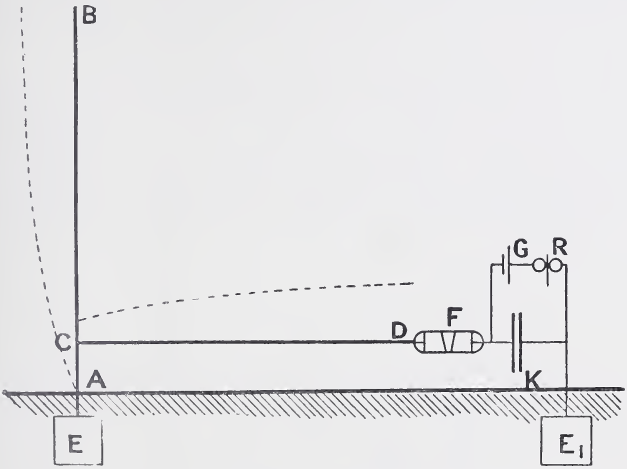


FIG. 29.—Slabo-Arco receiving antenna, AB; syntonic side wire, CD; coherer, F; condenser, K; relay, R; local cell, G; earth plates, E, E_1.

February 6, 1901, the horizontal wire is made to extend for a distance double the height of the vertical aerial, and the outer end of the horizontal wire is earthed at E_3, and the coherer inserted between an earth, E_2, and a half way point, B, on the horizontal wire (see Fig. 30).

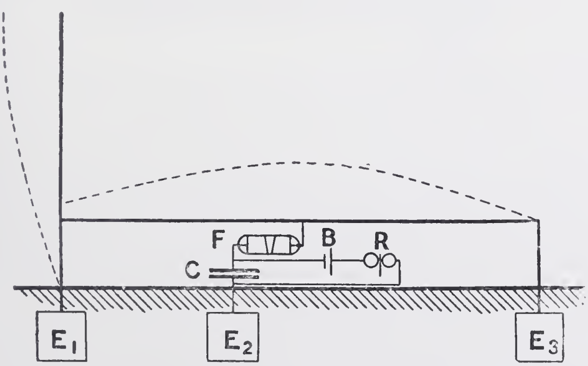


FIG. 30.—Another Slaby-Arco Arrangement of Receiving Apparatus with syntonic side wire of double length. Coherer, F; condenser, C; relay, R; working cell, B; earth plates, E_1, E_2, E_3.

In these diagrams the dotted lines represent by their distance from the aerial wires (firm lines) the amplitude of the potential oscillation at each point in the wire, and show, therefore, the position of the nodes and loops of potential.

The corresponding transmitter is described in the German patent, No. 131,586, applied for November 9, 1900, and consists of a vertical aerial, AB, and a pair of spark balls, S, interposed between a horizontal extension wire, CD, and the vertical antenna. The secondary terminals of the induction coil I are connected to the spark balls (see Fig. 31).

The operation of the receiving aerial is as follows :—

Referring to the diagram in Fig. 29, E represents the earth plate and AB the vertical aerial. The lateral wire CD is equal in length to the section CB of the vertical aerial, and F is the coherer tube placed at D, and a condenser, K, earthed at one side, is in series with it. The condenser is shunted by a single local cell, G, and a relay or recorder, R. When oscillations take place in the aerial, the

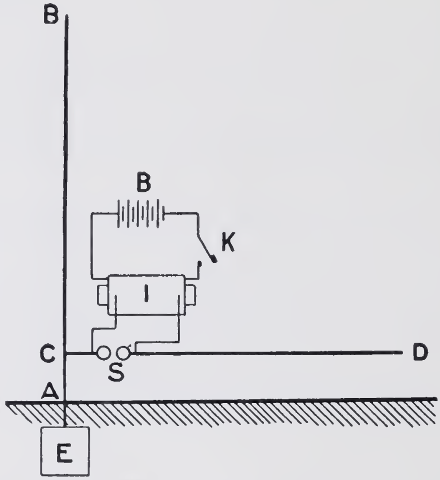


Fig. 31. Slaby-Arco transmitting antenna, CB ; side wire, CD ; spark balls, S ; induction coil, I ; earth plate, E ; battery, B ; key, K.

point D in the lateral wire is an antinode of potential. Hence the coherer gets the benefit of the maximum potential oscillations, and as soon as it becomes conductive the cell G sends a current through the relay R and coherer F, and down through the aerial earth plate E, and up again through the condenser earth plate E_1, so completing the circuit.

It is not necessary that the lateral wire CD should be laid out straight. It may be coiled in an open spiral (see Fig. 32), and somewhat shortened to compensate for increased inductance. In this form the open spiral CD becomes a means of exalting the potential oscillations at the point D, so that the amplitude is greater at D than at C. Professor Slaby, therefore, called a coil so adjusted a *multiplier*.

Associated with this receiving arrangement, we have the transmitting system, as shown in Fig. 31, where AB is the transmitting aerial, and S the spark balls, and CD the horizontal wire, which in the same manner need not be stretched out straight, but may be loosely coiled

into a spiral. The spark balls are connected to the secondary terminals of an induction coil, and oscillations are set up in the horizontal and vertical wires with an antinode of potential at the open ends.

The above arrangements, therefore, are well adapted for utilizing as aerials any two vertical wires or rods earthed at the lower end but insulated elsewhere, such as two lightning rods. Moreover, Slaby saw that it would be possible to adapt these arrangements to syntonic telegraphy. Let two transmitter aerials, AB and A′B′, be set up, one having an upper section 1·5 times the length of the other, each being provided with appropriate coiled side wires and interposed spark balls (see Fig. 33). Then let one receiving aerial, *ab*, be established at a distance having a height equal to AB. To this let two lateral wires be adapted, one of them, *bd*, of such a length that $bd = ab = \text{AB}$, and

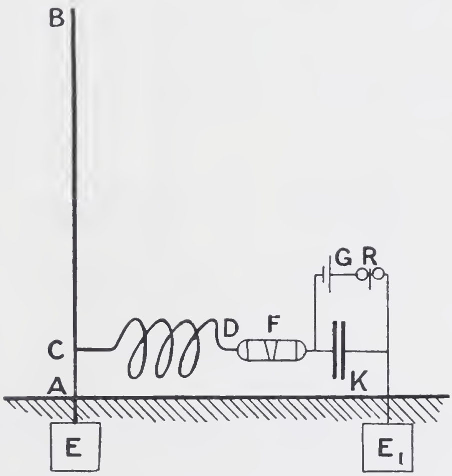


FIG. 32.—Alternative Slaby-Arco Receiving Arrangement, with side wire, CD, coiled into an open spiral.

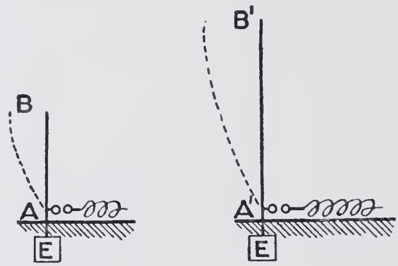
the other, *bf*, of such a length that $ab + bf = 2\text{A}'\text{B}'$. If then the fundamental oscillation of the aerial AB is excited, its radiation will set up oscillations in the section $ab + bd$ of the receiving aerial. If, however, the fundamental oscillations of the aerial A′B′ are excited, their radiation will cause the section $ab + bf$ to be excited. Accordingly, if coherers are put at the outer ends *d* and *f*, and earthed through condensers, which are also shunted by local cells and relays, we shall have a system of two transmitter rods and one receiving, which enables duplex simultaneous or syntonic telegraphy to be conducted.[32]

Professor Slaby made an exhibition of this method in a lecture given in Berlin on December 22, 1900, in the conference room of the General Electric Company of Berlin, in the presence of H.M. the Emperor of Germany. The lecture was entitled, "Syntonic and

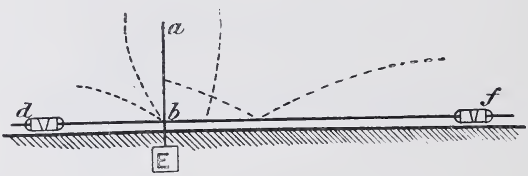
[32] See German Patent, No. 131,584, granted to the General Electrical Company of Berlin, application of November 9, 1900.

Multiple Spark Telegraphy."[33] In this demonstration simultaneous telegraphy was conducted between a transmitting station at the Technical High School at Charlottenburg, at Berlin, and the works of the General Electric Company, 2·5 miles, or 4 kilometres, distance, and also between the latter place and a cable manufactory at Oberschöneweide, 9·3 miles, or 14 kilometres, distance. The two wave lengths used were respectively 640 metres and 240 metres. Good independent simultaneous telegraphy was conducted.

Other variations of the horizontal wire arrangement of aerial devised by the same patentees are as follows: In the German patent, No. 127,730, of November 10, 1900, a lateral coiled wire is attached to a vertical aerial at a point a little way above the ground. This lateral coil has such a length that there is a node of potential at the



Transmitter No. 1. *Transmitter No.* 2.



Double receiving antenna.

FIG. 33.—Slaby-Arco Arrangements for Duplex Syntonic Telegraphy. The dotted lines in the diagrams denote the amplitude of the potential oscillations in the antennæ at the corresponding points.

centre and an antinode of potential at its outer end. Hence, if a coherer in series with a condenser is joined between the base of the aerial and the outer end of the lateral wire, it will be acted upon by the maximum difference of potential. The condenser is shunted as usual by a relay and local cell.

In a pendant patent, No. 130,122, of December 13, 1900, the condenser shunted by the relay and cell is transferred to the centre of the lateral wire, where there is a node of potential, as in that case it produces a less disturbance of the potential distribution.

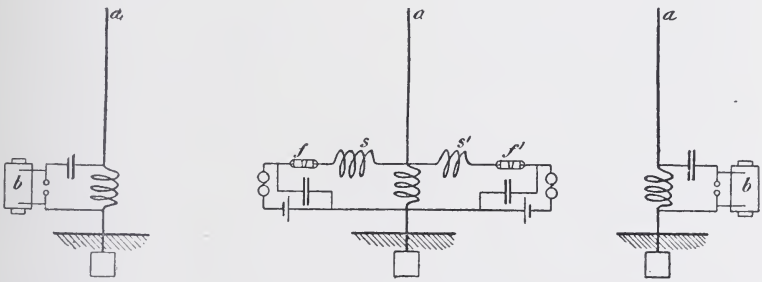
It will be seen on examining the arrangements of the above-described syntonic system of Slaby and Arco, that if we substitute one single earth plate for the two earth plates used in Fig. 32, the

[33] "Abgestimmte und Mehrfache Funkentelegraphie," by A. Slaby, see *Elektrotechnische Zeitschrift*, 1901, or *The Electrician*, January 18, 1901, vol. 46, p. 475.

oscillating circuits at the sending and receiving end each resolve themselves into a closed oscillating circuit containing a capacity, inductance, and either spark gap or coherer arranged in series, this oscillating circuit having one point connected to earth and the other to an aerial wire or open oscillating circuit which is in resonance with the closed circuit. Hence we arrive at the arrangement which is now generally called the direct-coupled aerial system. The practical arrangement of the Slaby-Arco system of multiple or syntonic telegraphy was, therefore, modified later on into the form shown in Fig. 34.

Each transmitter consists of a condenser suitable for working with high potentials, and this is connected in series with a variable inductance and the two joined to the spark balls of the secondary circuit of an induction coil. One end of this inductance coil is joined to an earth plate and the other end to an aerial wire.

The receiving circuit is very similar. In it we have an aerial wire connected to earth through an inductance coil, and to the terminals of this last-named coil are connected one, two, or three oscillatory circuits,

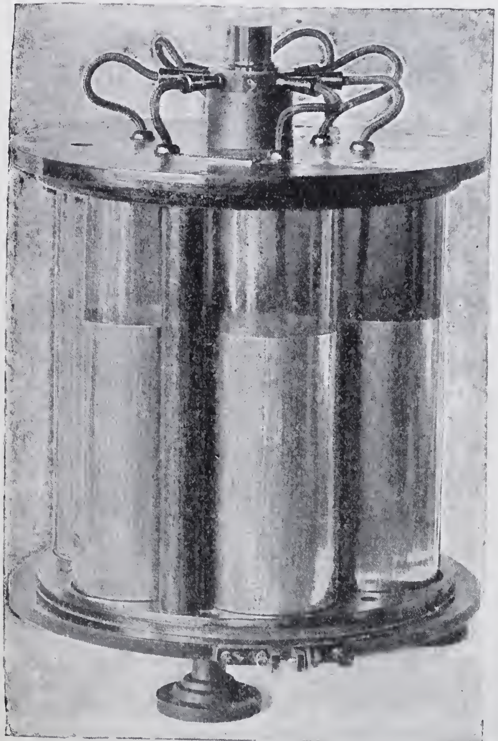


Transmitter No. 1. *Double receiving station.* *Transmitter No.* 2.

FIG. 34.—Scheme of Circuits of Slaby-Arco Apparatus for Duplex Syntonic Electric Wave Telegraphy, omitting Tuning Coils.

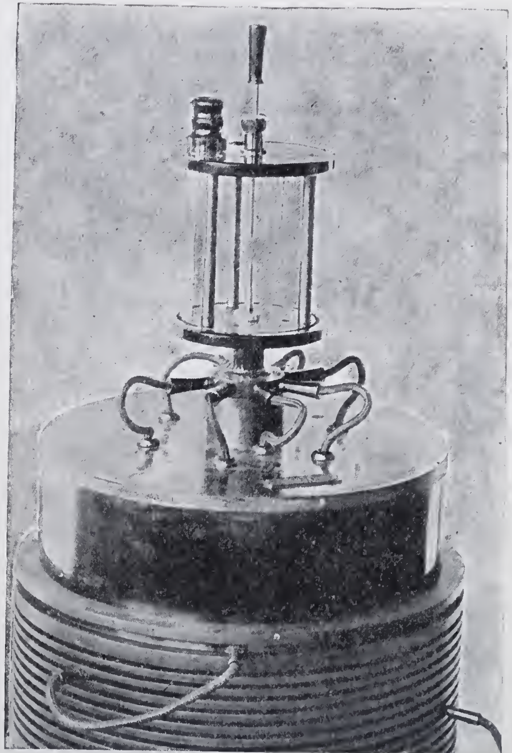
each of which consists of a variable inductance coil for syntonizing *s* or *s'*, a coherer, *f* or *f'*, and a condenser. A relay and local cell is connected across the terminals of each condenser.

The condenser in the transmitter circuit consists of a battery of five or six Leyden jars contained in an insulating vessel (see Fig. 35). The total capacity may be about 0·001 mfd. On the top of this is placed the adjustable spark gap, and round the vessel containing the Leyden jars is coiled the variable inductance coil, consisting of bare copper wire wound in a groove in an ebonite cylinder (see Figs. 36 and 37). The upper or adjustable spark ball is the earthed ball, and the spark gap condensers and inductance are joined in series. The aerial is connected to the end of the inductance furthest from the earthed spark ball. This oscillation circuit is excited by an induction coil giving a 25 cm. spark, and the primary current is interrupted by a mercury turbine break suspended in gimbals (see Fig. 38). On board ship the induction coil is fixed up against a bulkhead and the break suspended underneath the operating table. The appearance of the complete set is shown in Fig. 39 (see p. 574).



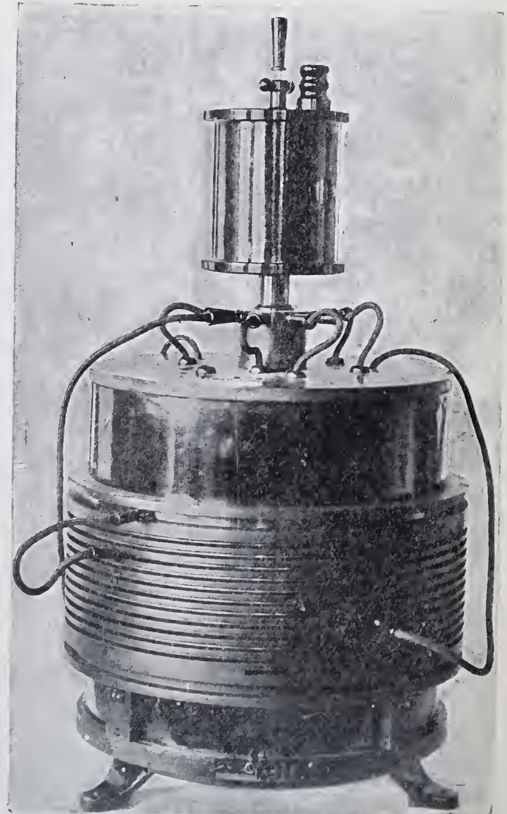
From "Traction and Transmission."

FIG. 35.—Battery of Leyden Jars forming the Condenser in Slaby-Arco Transmitter.



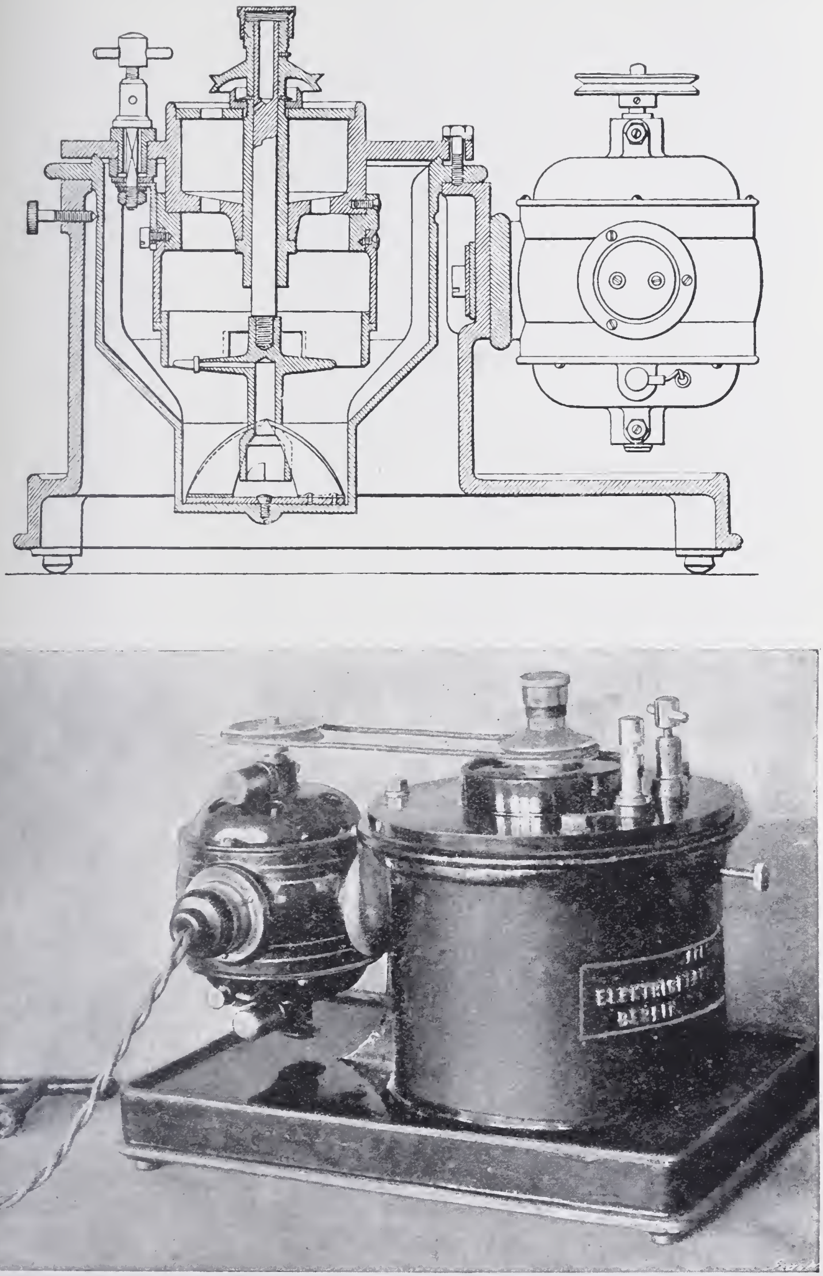
From "Traction and Transmission."

FIG. 36.—Adjustable Spark Discharger and Variable Inductance in Slaby-Arco Transmitter.



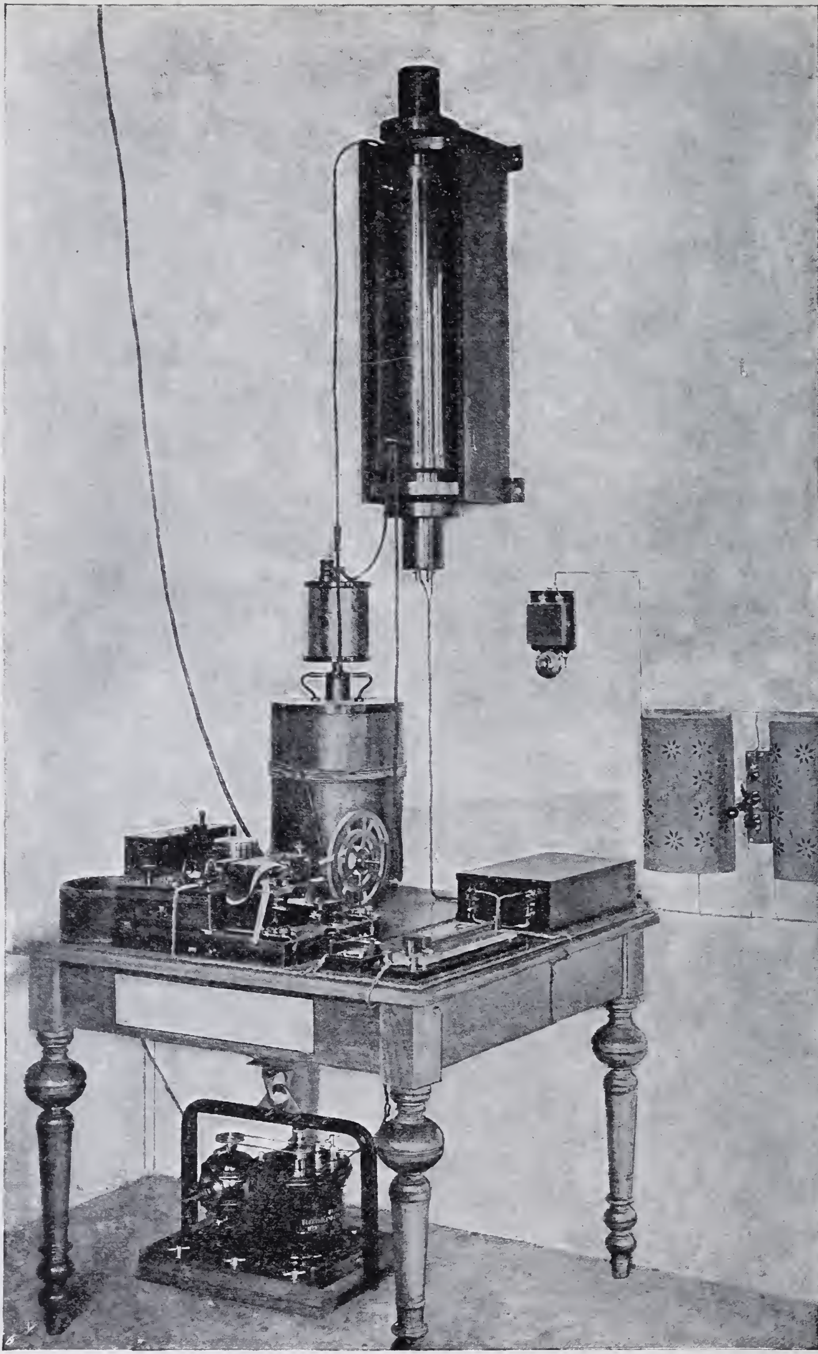
From "Traction and Transmission."

FIG. 37.—Discharger and Inductance Coil Enclosing Leyden Jars in Slaby-Arco Transmitter.



From "Traction and Transmission."

Fig. 38.—Sectional and Perspective View of Mercury Turbine Interrupter and Electric Motor used in the Slaby-Arco Transmitting Apparatus, as made by the General Electric Company of Berlin.



From "Traction and Transmission."

Fig. 39.—View of Complete Slaby-Arco Apparatus for Electric Wave Telegraphy, showing the Induction Coil fastened to the Wall and the Turbine Mercury Interrupter under the Table.

The coherer tube used resembles that of Marconi. It consists of a glass tube (see Fig. 40) exhausted of its air and containing two well-fitting bevelled silver plugs with ends in close apposition. Between them is a small quantity of nickel filings. The coherer is held in a clip so that it can be turned round to make the filings lie in a wider or narrower portion of the gap, and so vary the sensibility. The coherer is tapped by an automatic electromagnetic hammer.

The primary circuit of the induction coil contains a Morse key for signalling, with magnetic blow-out to stop sparkling, and the receiving circuit contains a relay and Morse inker.

In order to adjust the transmitter and receiver to syntonism, Count Arco devised a portable syntonizing coil, which allows any number of stations to be brought to the same "tune" or period. The arrangement is shown diagrammatically and objectively in Fig. 41.

It consists of a variable inductance coil and condenser, the condenser having a pair of adjustable spark balls connected to its terminals. When one transmitting station has been brought to resonance with any receiving station, the syntonizing coil is applied, as shown in the lower diagram (Fig. 41), to the base of the transmitting aerial *a*, and the inductance A of the syntonizer adjusted until the longest spark is obtained at the spark points *h*. The syntonizer is then removed to some other transmitter station, and the variable inductance

FIG. 40.—Metallic Filings Cymoscope used in Slaby-Arco Receiver.

of the transmitter is altered until the syntonizer gives a spark equally long when attached as shown in the diagram. This appliance is, however, only a rather rough form of cymometer, and better results can be obtained by measuring the wave lengths of the wave emitted by the transmitter and adjusting the inductance coil of the latter until the required wave length is obtained (see Chap. IX. § 4).

If the arrangement of Lodge and Muirhead, as described in their British specification, No. 11,348 of 1901 (see p. 562), is compared with that of Slaby and Arco just described as developed by the General Electric Company of Berlin, it will be seen that there is no essential difference between them. In each case we have a closed oscillatory circuit connected at one point to the earth and at another to an aerial. We may, in fact, say that no one has yet devised any form of transmitter and receiver for electric wave telegraphy which does not fall under one of the three following forms (see Fig. 41). First, the transmitter is either a simple insulated aerial wire with spark ball at the lower end, and a corresponding spark ball connected to an earth plate. This is the original arrangement of Marconi, and is now called the *plain aerial*. In the next place, the oscillations may be set up in a closed oscillatory circuit which is connected at one point to the earth and has an aerial wire in syntony with it connected to some other point. This is called the *direct-coupled aerial*, and is

the typical form of the arrangements of Lodge, Muirhead, and Slaby-Arco systems. In the third place, the aerial may be connected

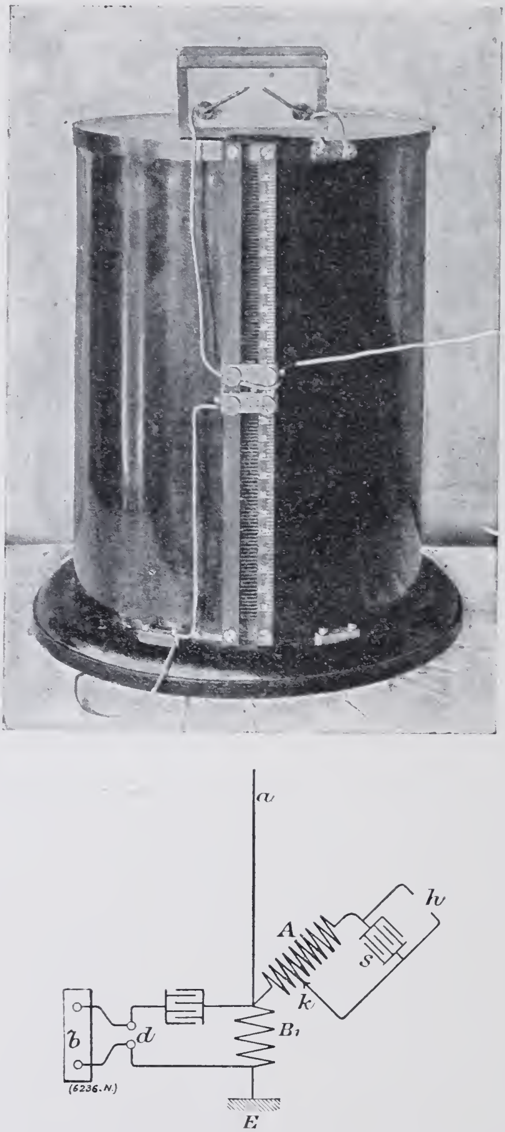


FIG. 41.—Arco Syntonizer for adjusting Time Periods of Antennæ. *a*, antenna; A, inductance coil; S, condenser; *h*, spark points; *k*, sliding contact.

inductively or through an oscillation transformer with the aerial. This is the method employed by Marconi, and, as we shall see in the next section, also by Braun. There is no essential difference between

the so-called direct-coupled and inductively-coupled methods. In the one case an autotransformer or single coil transformer connects the antenna to the energizing circuit. In the other case a two-coil transformer is employed.

In addition to the arrangements above described, Slaby and Arco devised also forms of closed loop receiver and transmitter aerial, to which reference has already been made (see Chap. IV. § 8).

If a closed oscillatory circuit is formed consisting of a condenser, loop of wire, and spark gap, we may set up oscillations in it by connecting the spark balls to an induction coil. We have in this case, however, no radiation if the length of the loop, compared with its fundamental wave length, is such that the current is at all points in the same direction at the same instant.

Slaby and Arco found that if the loop is constructed with unequal inductance on its two sides, and connected to the earth at one point, then harmonic oscillations can be set up in it such that there is a node of potential at the earthed end and an antinode or loop at the upper end. In this case the loop acts as if it were two simple Marconi aerials connected together at the top. The arrangements adopted in practice for the transmitter loop, as shown in the German patent specification of Slaby and Arco, No. 133,718, applied for November 4, 1899, are as follows:—

A condenser has one terminal connected to earth and the other to the lower spark ball of a discharger. The upper spark ball is connected to an aerial composed of a group of parallel wires, and the upper end of this aerial is connected to earth through an inductance coil or wire with considerable inductance.

One way in which we may view the operation of this loop antenna is to consider that the inductance connected between the upper end of the aerial and the earth, whilst not offering impedance enough to prevent the relatively slow charging of the aerial and condenser, acts like a perfect insulation toward the high frequency oscillations set up at each discharge.

Another of these looped aerials is described by Slaby and Arco in their German patent, No. 124,154, dated December 23, 1898. In one form the transmitting loop consists of a vertical rectangular loop of wire having a condenser in one side and a pair of spark balls below it, the loop being earthed at the bottom. If the fundamental oscillation is set up in the loop it does not radiate, for the reasons explained in Chap. IV. § 8 of this treatise. If, however, a harmonic oscillation is set up so that the upper end of the loop is an antinode of potential and the lower end a node, radiation is emitted from it. Corresponding to this looped transmitter the patentees described in the same specification a looped receiving aerial in which the coherer and working cell and relay are placed in one side of the loop, and, if need be, a condenser arranged in parallel with the other side. The lower end of the loop is earthed. The patentees say that it has been shown by experiment that such a transmitting loop produces different effects in different directions, and for the best effect it is necessary to erect the transmitting and receiving loops so that their planes are parallel and at right angles to the line joining their centres.

The General Electric Company of Berlin also described at a later

date, in a German patent, No. 129,892, dated October 16, 1900, a looped receiving aerial. If two simple straight aerials are set up side by side, and acted upon by incident electromagnetic waves of suitable period, they would exhibit no difference of potential between points at equal height from the ground, and a coherer joined in between these points would not be affected. If one of the aerials is lengthened at the bottom by a loop equal in length to its own height, and if the two aerials are connected together at the top and earthed at one point (see Fig. 42), the coherer, joined across as shown, will be affected strongly. We may cause a telegraphic printing instrument to record as usual by inserting a condenser shunted by a relay and local cell in series with the coherer, and operating the printer by the relay. The inventors say that the earthing in this case is not necessary;

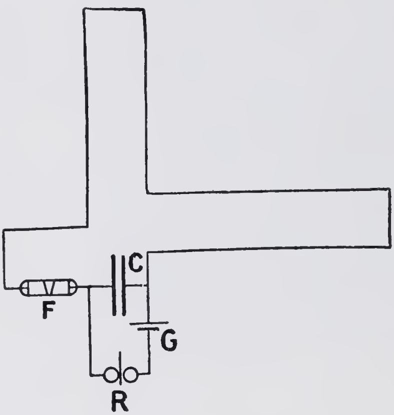


FIG. 42.—Closed Circuit Receiving Antenna of the General Electric Company, Berlin. F, coherer; C, condenser; R, relay; G, cell.

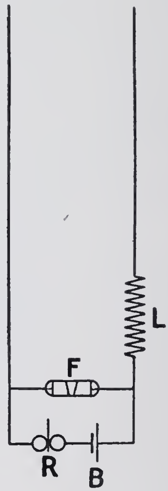


FIG. 43.—Parallel Antennæ, one having inductance, L, in series with it.

also that by the use of the loop circuit disturbances due to atmospheric electricity are avoided. They also gave a diagram in which two aerials not connected at the top act as plates of a condenser to each other. In one aerial wire an inductance coil is inserted (see Fig. 43), and a coherer shunted by a working cell, and a relay is connected across between the two aerials at the bottom.

Slaby and Arco, or their patent assignees, the General Electric Company of Berlin, applied for several German patents describing variations or combinations of the above forms of aerials.

In some cases they made use of the exalted potential, generated at the extremity of a resonant coil, to charge another aerial of the straight or looped form.

Thus the arrangement of transmitter described in the German patent, No. 126,273, of February 28, 1901, is interesting. Oscillations

are set up in a closed circuit containing a condenser, C, and inductance, L, and to one point on this circuit the end of a resonant or multiplier coil, M, is attached, and the exalted potential at the other end of this last coil is caused to charge a loop transmitting aerial, A (see Fig. 44).

Another form of this circuit was described by them previously in a German patent, class 21A, registered number 7775, applied for December 10, 1900. The action of these nearly closed circuit or loop antenna, whether used as radiators or receivers, was not clearly understood at this date (1900), and the reader is referred to Chap. VIII. § 3, for a fuller discussion of them.

A number of minor improvements by Slaby and Arco, some of

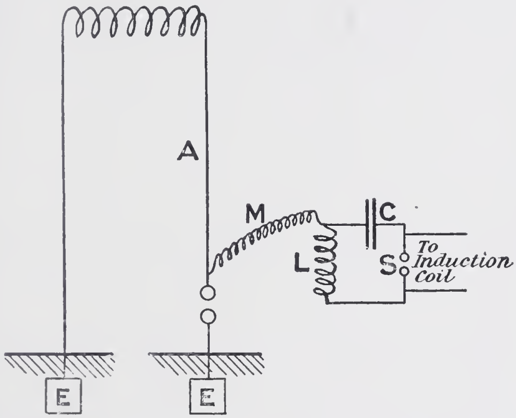


FIG. 44.—Loop Transmitting Antenna charged by means of a Tension Multiplying Coil, M, from a Closed Condenser Circuit, C, L, S.

which, however, were in use by Marconi previously, are described in other German patents, as follows:—

No. 113,285, of April 25, 1893.—This is an arrangement of the receiving apparatus for wireless telegraphy for the purpose of avoiding disturbances by the spark at the tapper, such that by an interruption of the local circuit through the coherer and that of the tapper magnet just before the hammer strikes the tube the spark at the armature contacts of the tapper magnet is over before the blow occurs, and thus at that instant no current is passing through the tube. Marconi, however, effects the required result quite satisfactorily by means of the choking coils he inserts in the connections leading from the coherer to the relay and local cell.

No. 116,071, of February 9, 1900.—In a receiving arrangement consisting of a coherer actuating a relay and Morse printer, the coherer is affixed to the armature of the Morse printer, instead of being tapped by a separate tapper. This arrangement, however, does not afford the required range of adjustment of the decohering blow.

No. 116,113, of March 24, 1900.—This is a patent for making the gap between the plugs in a coherer of the Marconi type wedge shape by bevelling the plugs so that by turning the tube round the sensibility of the tube can be altered within limits. This device has been patented many times by various inventors.

No. 129,017, of April 19, 1901.—This is a patent for a Morse signalling key for use in the primary circuit of an induction coil, provided with a permanent magnet to effect a magnetic blow-out of the spark.

13. Contributions of Professor F. Braun to Electromagnetic

Wave Telegraphy.—Professor Ferdinand Braun, of the University of Strasburg, has devoted considerable attention to the subject of wireless telegraphy by electromagnetic waves. His first German patent on the subject was applied for on October 14, 1898, No. 111,578.[34] He begins the specification by arbitrarily dividing electric oscillations into three groups—

(i.) Those created by mechanical means.
(ii.) Those produced by the discharge of Leyden jars.
(iii.) Those generated by Hertzian oscillations.

He states that the last variety alone have hitherto been utilized for wireless telegraphy. This division is, however, not founded upon any true scientific distinction between these various kinds of oscillations. The frequency of the oscillations, and therefore the length of wave sent out from a connected antenna, is merely a question of the capacity of the condenser or antenna used, and the inductance through which it is discharged, and a Hertz oscillator and Leyden

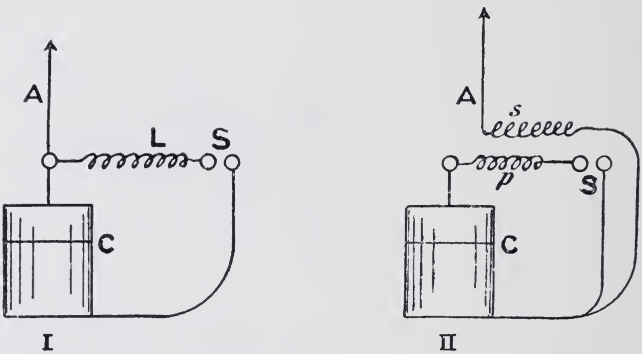


FIG. 45.—Diagrams taken from German Patent Specification, No. 111,578 of 1898, of Dr. F. Braun. C, Leyden jar; S, spark balls; A, antenna.

jar are both special forms of condensers. Braun proposed in this specification, as a method of wave production, to include in the circuit of a Leyden jar, C, a spark gap, S, and an inductance coil, L, and, furthermore, to attach to one surface of the condenser an aerial wire, A, as a radiator (see I, Fig. 45). This arrangement is now called a direct-coupled aerial. Braun also proposes in the same specification to couple together the oscillatory circuit of the jar C and that of the aerial A inductively by means of an air core transformer (p, s) (see II, Fig. 45). This is now called the inductive coupling. The two diagrams in Fig. 45 are taken from Braun's specification. Braun, however, says nothing in the above-named specification as to the necessity for any relation between the natural time period of oscillation of his closed and open circuits.

There is nothing in this first specification of Braun to show that he was aware of the reaction which the two circuits, open and closed, he couples together excite on each other, although it had been already mathematically discussed by A. Oberbeck (see Chap. III. § 11).

[34] The equivalent British patent specification is No. 1862, of January 26, 1899.

These circuits are, in fact, like two pendulums. Each has its own independent natural time period of oscillation when vibrating alone, and they may be coupled together in various ways. The mere haphazard coupling of two circuits, one a closed and the other an open or radiative circuit, does not necessarily result in the production of an oscillator which is, telegraphically speaking, more effective than the simple linear oscillator of Marconi.

Braun's suggested direct coupling of an aerial wire with a nearly closed oscillation circuit, consisting of a Leyden jar and associated inductance and spark balls, compared with the simple insulated conductor or aerial of Marconi, separated from the earth by a spark gap, does not produce a radiator having any special advantages unless there is a syntonism between the two coupled circuits. Neither is the inductive coupling of any special advantage unless the oscillation transformer is constructed in a particular manner. There is some indication in the opening remarks of Braun's specification, that he considered the real novelty in his invention to be the employment of the oscillations or discharges of a Leyden jar to create electric waves for telegraphic purposes, in place of the oscillations established directly of a simple linear or open circuit radiator containing a spark gap. It may be noted, however, that Lodge had previously in his British patent, No. 11,575, of 1897, proposed to employ the discharge of a Leyden jar to excite oscillations for radiotelegraphy. There are only two modes of coupling an open and closed oscillatory circuit which have any technical value. First, we may couple together the circuits in such a manner that a single pure oscillation or one single period of vibration is forced upon the aerial or radiator, not its own natural period, but that of the actuating closed circuit. Secondly, we may couple together circuits which have the same free natural time period when separate, and thus establish a syntonism between the circuits which, under the condition of a somewhat "loose coupling," results in the radiation of waves of two different wave lengths.

The first mode of operation was described by J. S. Stone (see § 20 of this chapter), and the second was discovered and worked out practically by Marconi. It has sometimes been suggested that Marconi availed himself of Braun's prior invention, but in truth his (Marconi's) investigations were carried on quite independently, and conducted to a more practical issue than those of Braun—at least up to the date when the latter secured his first German and equivalent British patent, No. 1862, of January 26, 1899.

Marconi provided at a little later date, in his British specification, No. 7777 of 1900, the definite information necessary for utilizing the inductive coupling, not simply as an isolated suggestion, but as part and parcel of a complete and practically operative system of syntonic electric wave telegraphy.

The mere fact that electrical oscillations produced by the discharge of a Leyden jar could be transformed in potential by an air core transformer, was already well known, and had been employed as far back as 1850 by Joseph Henry, and later by Tesla, Elihu Thomson, and others in 1890 and 1891. The mathematical theory of such oscillation transformers containing inductance and capacity in each circuit, commonly called Tesla coils, had been worked out some time

previously to the date of Braun's patent application by A. Oberbeck, M. Wien, and others.[35]

It was not even novel in 1898 to create induced electric oscillations in an open electric oscillatory circuit by inductively coupling it to another oscillatory circuit containing capacity inductance and a spark gap. In a lecture given in 1891, before the American Institute of Electrical Engineers, reported in a book entitled the "Inventions, Researches, and Writings of Nikola Tesla," published in New York in 1894, many diagrams and descriptions are given of oscillation transformers consisting of closed and open oscillatory circuits inductively coupled. On page 328 of the above-named book, in Fig. 175, is shown a diagram indicating an oscillation transformer of the Tesla type, the primary circuit consisting of a coil, through which the oscillatory discharge of a Leyden jar is sent, the secondary circuit consisting of a coil wound over the primary circuit, not closed, but furnished with extension wires, each ending in large plates, the whole secondary circuit thus forming an open oscillatory circuit of the Hertz type; many other diagrams are given in the same book which show that at that date (1894) Tesla was accustomed to employ an air core oscillation transformer to couple together inductively an open or radiative circuit and a closed oscillatory circuit through which the discharge of a Leyden jar was sent.

Lodge had also long previously shown that if a Leyden jar was provided with two discharge circuits, one called the A circuit and the other called the B circuit, then when an oscillatory discharge was set up in the A circuit it caused a sympathetic discharge in the B circuit, provided that there was a syntony between the time periods of the two circuits, so that one was equal to or a harmonic of the other. Lodge, however, did not propose to set in inductive connection two oscillatory circuits, one an open circuit or wire having capacity with reference to the earth, and the other a closed circuit having an equal or harmonically related time period.

It will be seen, however, that from the researches of Lodge, Slaby, Arco, and Braun has been developed the practical form of direct-coupled closed and open oscillatory circuits, which is a widely used type of transmitter in connection with wireless telegraphy. On the other hand, inductive coupling of an open and closed circuit, as described by Tesla and Braun, was brought by Marconi into a condition to be of real practical use in wireless telegraphy when he (Marconi) invented the proper form of oscillation transformer for coupling inductively his aerial radiator or vertical wire to a closed oscillation circuit of syntonic period.

There is, however, no fundamental difference between the forms of transmitter or receiver circuit in which a single coil or a double coil transformer respectively interconnect the antenna and the energy stirring condenser circuit. In both cases Marconi's method of syntonization of these circuits must be employed to obtain practical results.

The double-coil coupling offers certain advantages not possessed by the single-coil. We can inductively couple together the circuits

[35] See A. Oberbeck, *Wied. Ann.*, 1895, vol. 55, p. 623; also Geitler, *Wied. Ann.*, 1895, vol. 55, p. 513; and Max. Wien, *Wied. Ann.*, 1897, vol. 61, p. 151; also *Ann. der Physik* (4), 1902, vol. 8, p. 686.

"loosely" or "closely," and in general the inductive coupling gives us a facility for storing up larger amounts of electric energy to be released and imparted to the open circuit, and thence radiated as electric waves.

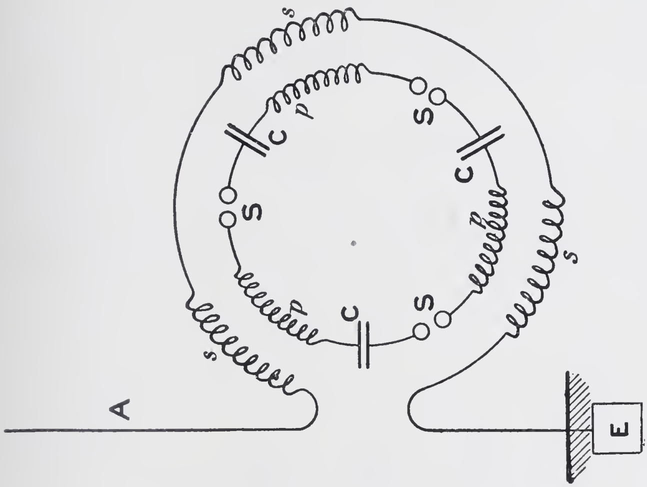


FIG. 48.—Inductive Coupling of Antenna and Condenser Circuits in Series. A, antenna; C, condensers; S, spark balls; p, s, oscillation transformers. (Braun.)

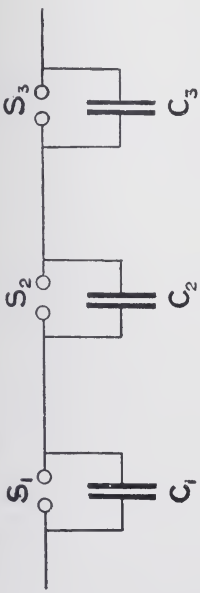


FIG. 46.—Arrangement of Condensers, C_1, C_2, C_3, and Spark Balls, S_1, S_2, S_3 in Series. (Braun.)

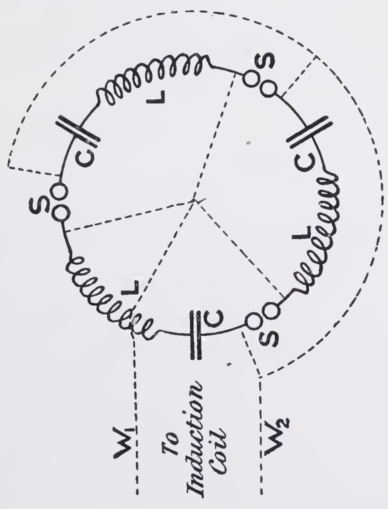


FIG. 47.—C, condensers; L, inductances; S, spark balls, arranged in series. (Braun.)

In a later German specification, No. 109,378, of January 26, 1899, Braun proposed to place Leyden jars, C_1, C_2, C_3, each with its own spark balls, S_1, S_2, S_3, these being joined in series for the sake of

accumulating voltage[36] (see Fig. 46). If we have n Leyden jars, each of capacity C, which will bear charging without damage to a potential V, we can arrange these jars either in parallel or series. In the first case we can charge the n jars each to a potential V, and accumulate a store of energy equal to $\frac{n}{2}CV^2$ in the n jars. In the next place we may charge the whole of the n jars in series to a potential nV, and accumulate a store of energy also equal to $\frac{1}{2}\cdot\frac{C}{n}(nV)^2$ or to $\frac{n}{2}CV^2$. The energy storage is the same in both cases, but the time period of oscillation is very different. Also there is a practical objection to the use of a long spark. We soon reach the limit at which the spark becomes non-oscillatory, and the damping by spark resistance very large. Braun, therefore, proposed to arrange the n jars

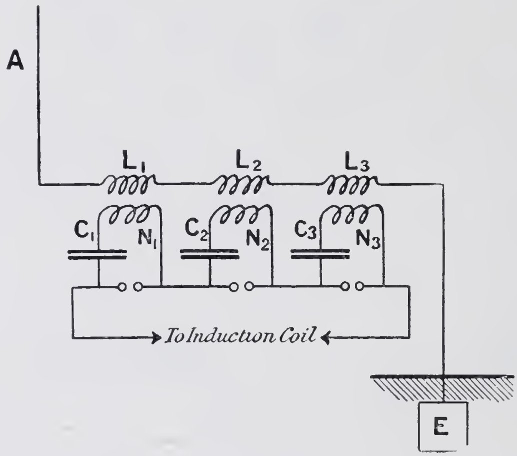


FIG. 49.—Arrangement of a Transmitter Circuit. (Braun.)

as in Fig 46, each with its own discharge circuit, so that whilst a total potential difference nV could be used in charging, and a total energy $\frac{n}{2}CV^2$ be stored up, equal to n times that in one jar, the time period of oscillation would not be changed, but each condenser would discharge through its own short spark gap. He proposed to employ the oscillations so created to generate inductively others in a secondary circuit, as shown in Fig. 49.

Another of Professor Braun's arrangements is shown in Fig. 47. In this a number of condensers, C, each having an associated inductance, L, are arranged in series with spark gaps, S, between. These condensers are all charged in parallel from two circuits, $-W_1$ and $+W_2$, maintained in connection with the secondary terminals of an induction coil. When the potential between the spark balls rises to the breakdown point fixed by the length of the spark gap, the

[36] See F. Braun, British Specification, No. 5104, of March 8, 1899.

condensers discharge into one another with oscillations. The time period of one condenser and inductance alone would be equal to $2\pi\sqrt{CL}$. The time period of the n condensers and inductances in series is just the same, being equal to $2\pi\sqrt{\frac{C}{n}.nL}$. In the last case, however, the energy storage is n times that in a single condenser charged to the same potential. Braun associates this closed compound oscillatory circuit with an open radiative one, either directly coupled or inductively coupled.

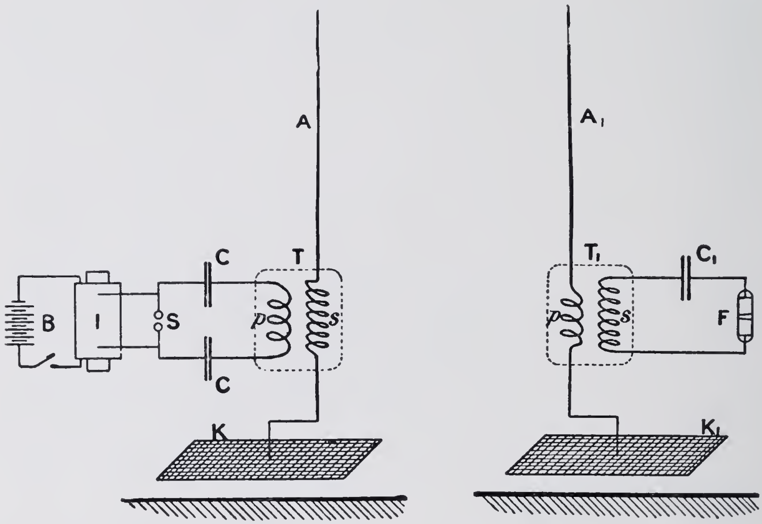
In another arrangement (see Fig. 48) a number of condensers are charged in series, as in Fig. 48, and each discharges through its own inductive circuit and spark gap, the circuit being the primary coil p of an air core transformer. The secondary circuits s of all these transformers are joined in series with each other, and the series interposed between an aerial, A, and the earth, E. The object of this arrangement is to secure a high potential or electromotive force in the radiative circuit, and yet to keep the wave length moderately small, and, above all, the damping due to spark resistance small. An alternative arrangement is shown in Fig. 49. The inventor is thus able to secure energetic trains of slightly damped waves. The separate condenser circuits, each consisting of condenser, spark gap, and inductance, may be charged in parallel from a constant supply, and the secondary oscillations induced by these discharges added together, as regards electromotive force, by joining the secondary circuits in series with an aerial.

14. The Braun-Siemens Practical System.—In bringing his devices and improvements in wireless telegraphy into practical form, Professor F. Braun associated himself with the firm of Siemens and Halske, of Berlin, just as Professor Slaby and Count Von Arco placed their inventions in the hands of the Allgemeine Elektricitäts Gesellschaft (The General Electric Company), of Berlin.

Braun's methods finally took the following form. At the transmitting end an induction coil, I (see Fig. 50), had its secondary terminals connected to two spark balls, S, and these, again, were connected by two condensers, C, C_1, in series with the primary circuit p of an oscillation transformer, T. The secondary circuit s of this oscillation transformer was inserted in between the aerial A and a large cylinder, K, acting as a balancing capacity, which took the place of the earth.

In practical apparatus Braun employed as the primary condenser a collection of glass tubes partly coated on both sides with silver or tinfoil, so as to form tubular Leyden jars of small capacity, and more or less of these were associated in parallel as required (see Fig. 51) (see p. 587). The large capacity K to which the base of the aerial is connected consists of a metal cylinder (see Fig. 56). The sending oscillation transformer consisted of a primary circuit of very low resistance of very few turns, having a secondary circuit wound over it, the two being placed in an oil bath (see Fig. 52). The primary circuit of the charging induction coil contained a Wehnelt interrupter (see Figs. 53 and 54) and a Morse key with magnetic blow-out. At the receiving end an oscillation transformer had one circuit inserted in between the aerial wire and the large capacity representing the earth. The other circuit was connected through a condenser with a coherer.

This consisted in one form of a tube with polished steel adjusted plug electrodes containing between them steel powder. The sensibility was varied by a small ring magnet. Some form of tapping arrangement was employed to decohere the steel filings. The sensitive tube was shunted as usual with a relay and local cell, and the relay connected with a Morse printing instrument and local battery. The receiving arrangement thus contains all the essential elements of Marconi's system of wireless telegraphy, but modified by the use of an insulated capacity in place of the earth connections. In some cases a steel carbon microphone used in series with a single cell and telephone has been employed as a detector in connection with the Braun-Siemens



Transmitter station. *Receiving station.*

FIG. 50.—Inductively Coupled Antennæ as used for Electric Wave Telegraphy. I, induction coil; S, spark gap; C, C_1, condensers; T, T_1, oscillation transformers; A, A_1, antennæ; F, sensitive tube, or coherer; K, K_1, balancing capacities. The Tuning Coils in the Antenna Circuits are omitted.

stations. The whole arrangement of the station is shown in Fig. 55 (see p. 588).

Braun tried his methods in the summers of 1899 and 1900 between Cuxhaven and Heligoland, a distance of 63 kilometres (40 miles), using aerial wires 30 metres high, and maintained his transmitting arrangement to be superior to that employed by Marconi. The comparison, however, which the German writers and inventors at that date invariably insisted upon making was to take as typical of Marconi's methods the original single wire-aerial transmitter of Marconi, direct connected to one spark ball of the induction coil, the other ball being earthed.[37] Marconi had advanced far beyond this stage at the end of 1899 and beginning of 1900, and was already employing

[37] See remarks by Prof. F. Braun in *The Electrician*, March 15, 1901, vol. 46, p. 778.

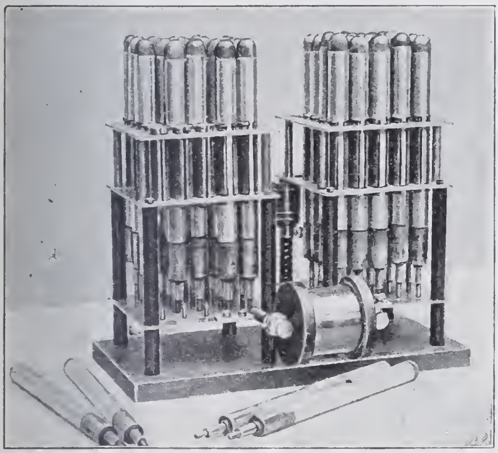


FIG. 51.—Leyden Jars or Condenser Tubes for Braun Transmitter.

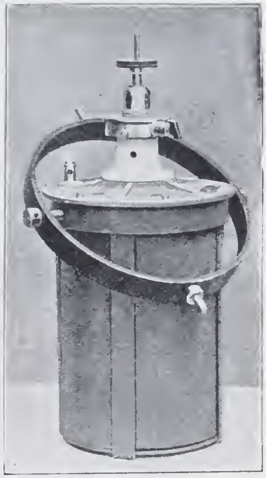


FIG. 53.—Wehnelt Break.

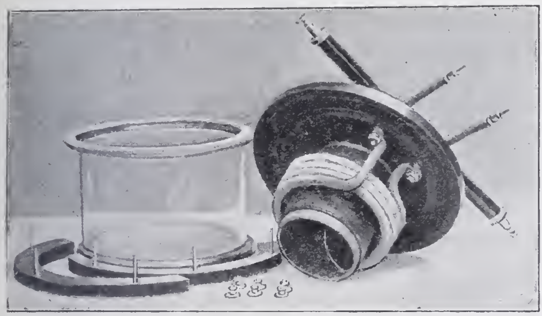


FIG. 52.—Oscillation Transformer in Transmitter Circuit.
From "The Electrical Review."

FIG. 54.—Adjustable Anode of Wehnelt Break.

Appliances used in the Transmitter Circuit of Braun - Siemens Electric Wave Telegraphic Apparatus.

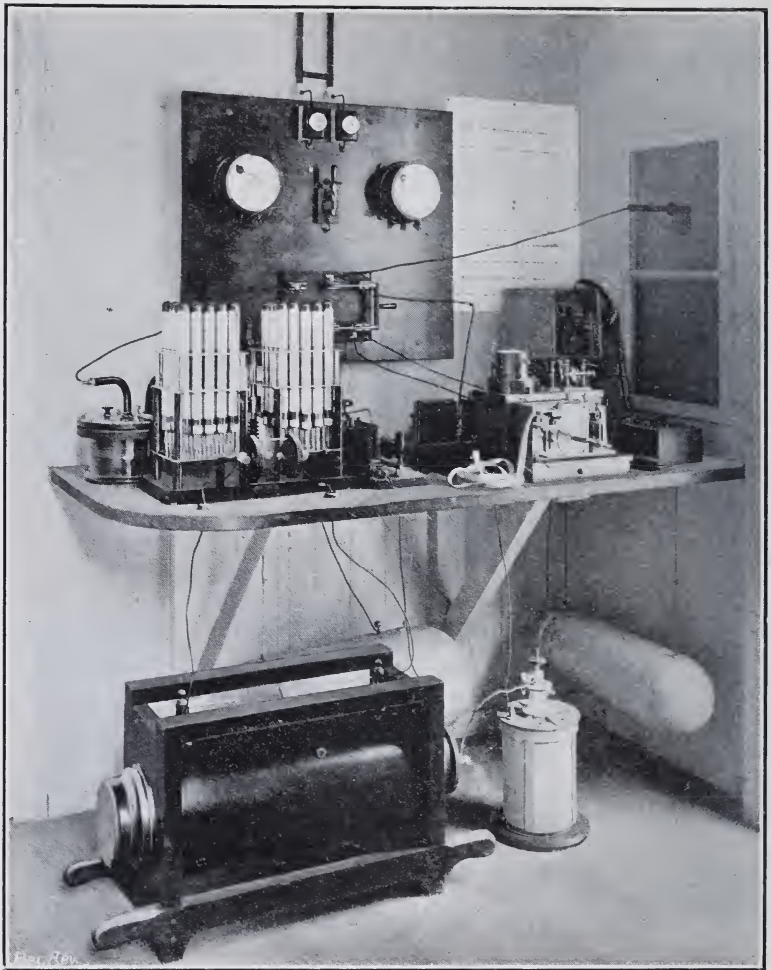


FIG. 55.—Arrangement of Braun-Siemens Wireless Telegraph Station.

FIG. 56.—Balancing Capacities used instead of Earth Connections in Braun-Siemens Transmitter and Receiver.

From "The Electrical Review."

the inductively coupled aerial with full knowledge of the conditions under which the best results could be obtained.[38]

15. The Telefunken System.—In the summer of 1903 the methods and inventions of Slaby, Von Arco, and the Allgemeine Elektricitäts Gesellschaft in Berlin, and those of Braun and Siemens and Halske, were amalgamated into a single company for conducting wireless telegraphy, and entitled the "Gesellschaft für Drahtlose Telegraphie," operating a system called the *Telefunken* system.

In the methods now adopted in this system there has been a return to the direct-coupled arrangement of the transmitter circuits and to telephonic methods of reception, as being in general more rapid than those employing a coherer and Morse printer. Also in

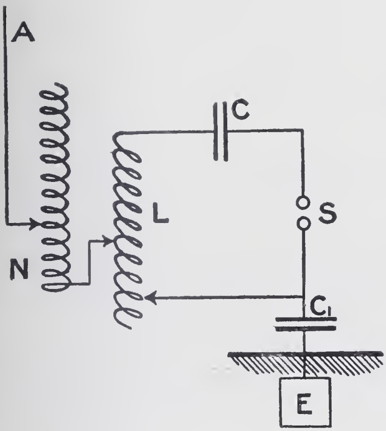


Fig. 57.—Arrangement of Apparatus in the Telefunken Transmitter. A, antenna; N, L, adjustable inductances; C, C_1, condensers.

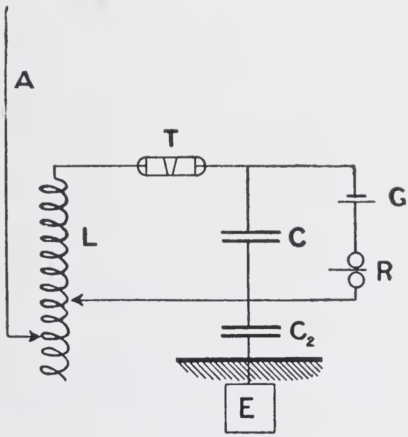


Fig. 58.—Arrangement of Apparatus in Circuit of Telefunken Receiver. A, antenna; L, adjustable inductance; T, coherer; R, relay; C, C_2, condensers.

most cases an earth connection is employed at the transmitting end. In some cases the simple earthed aerial with lateral extension is used as transmitter. In place, however, of a single pair of spark balls and a single spark gap a number of spark balls in series are employed, yielding a number of discharge sparks in series. In this manner large potentials can be employed and yet the dissipation of energy resulting from long sparks avoided, since the resistance of the spark increases very rapidly with its length. By this simple addition the Slaby-Arco transmitter is said to be capable of working over sea distances of 250 kilometres, with aerials only 32 metres high, and an energy expenditure of 90 watts in the induction coil.[39]

[38] We are not concerned here with questions of priority, but reference may be made to *The Electrician*, April 15, 1904, vol. 52, p. 1033, for a statement by Prof. F. Braun on his own work and his claims for it.

[39] See Otto Jentsch, "Telegraphie und Telephonie ohne Draht," p. 127. Berlin, 1904.

Also a direct-coupled aerial with closed condenser circuit is employed in this system. Variable inductance coils are inserted both in the condenser and aerial circuits for the sake of bringing the two circuits to resonance (see Fig. 57). The closed circuit is earthed through a large condenser. The receiving circuits used are of two types, one with a direct-coupled aerial (see Fig. 58), and another with an oscillation transformer inserted between the aerial and the closed circuit containing the wave detector (see Fig. 59). The cymoscope actually employed is either a metallic filings tube, having the bevelled plugs and filings enclosed in vacuum, or else an electrolytic detector, such as that of Schloemilch. If the metallic filings tube is employed, then the usual Marconi arrangements of tapper, relay, and Morse

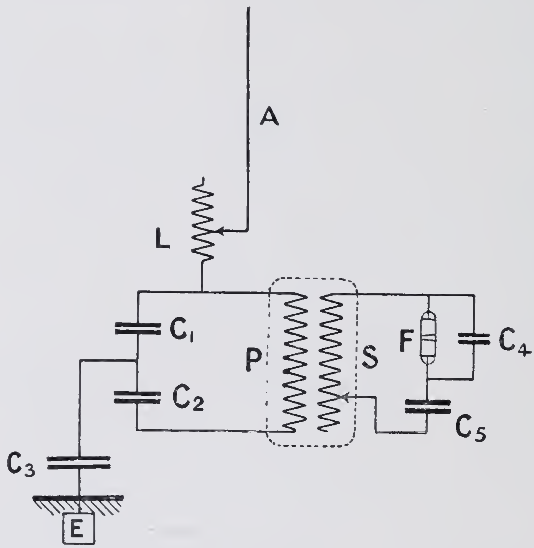


Fig. 59.—Alternative Arrangement of Apparatus in Telefunken Receiver. P, S, oscillation transformer; C_1, C_2, C_3, C_4, C_5, condensers.

printer are associated with it. If the electrolytic detector is used, then the telephonic method of reception is employed (see Fig. 60).

At the transmitting end an induction coil is used to charge the oscillating circuit. This is actuated by means of an alternating current, so that no interrupter is required. On board ship a rotating commutator is added so as to convert the ordinary continuous current used for the ship electric lighting into an alternating current having a frequency of about 50. In the primary circuit of the induction coil is inserted a Morse key, constructed as follows: The depression of the key brings together the platinum contacts, one on an elastic metal slip, M, carrying an iron armature and the other on the pole of an alternating electromagnet, E, through the coils of which the primary current of the induction coil flows. Hence, when the key is depressed this last circuit is closed and the attraction of the excited electromagnet on the armature keeps the circuit closed, even although the

key is raised (see Fig. 61). When, however, the alternating current passes through its zero value the armature flies up and the primary current is broken without spark.

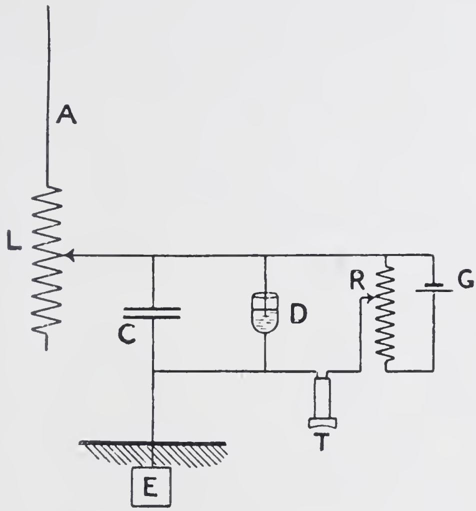


Fig. 60.—Telephonic Method of Reception as used in Telefunken System. A, antenna; L, adjustable inductance; D, electrolytic detector; T, telephone; G, battery; R, sliding resistance.

The oscillation transformer in the receiving circuit is "loosely coupled." Three types are employed, the secondary circuits being wound suitably for wave lengths of 50 to 200 metres, 200 to 600

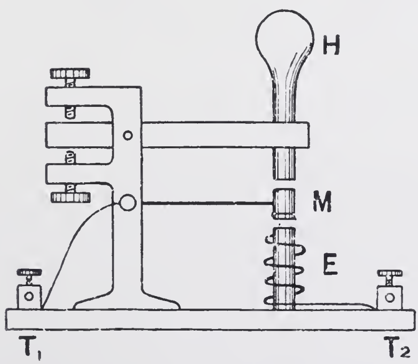


Fig. 61.—Non-sparking Key used with Alternating Currents in Telefunken Transmitter. E, electromagnet; M, intermediate contact.

metres, and 600 to 3000 metres, so that by change of connections the effective length of secondary circuit can be varied.

When the electrolytic detector is employed, the receiving circuit arrangements are as shown in Fig. 60.

16. Contributions of the Author to Wireless Telegraphy, 1900 to 1906.—The author's contributions to practical wireless telegraphy have consisted partly in the design of instruments for the exact measurement of electromagnetic waves of long wave length and in devices for their detection, and partly in improvements in apparatus for producing powerful electric waves by the discharge of large condensers, energized by means of alternating current transformers, connected to high tension alternators. One of these power wave generating arrangements is described in his British specification, No. 18,865, October, 22, 1900. In this arrangement an alternator, A (see Fig. 62), carries upon a prolongation of its shaft a revolving arm, x, insulated from the earth, and also an insulating cylinder or disc, D, having two contact plates laid upon a portion of its circumference. The revolving arm moves between two curved sectors, C_1, C_2, a knob

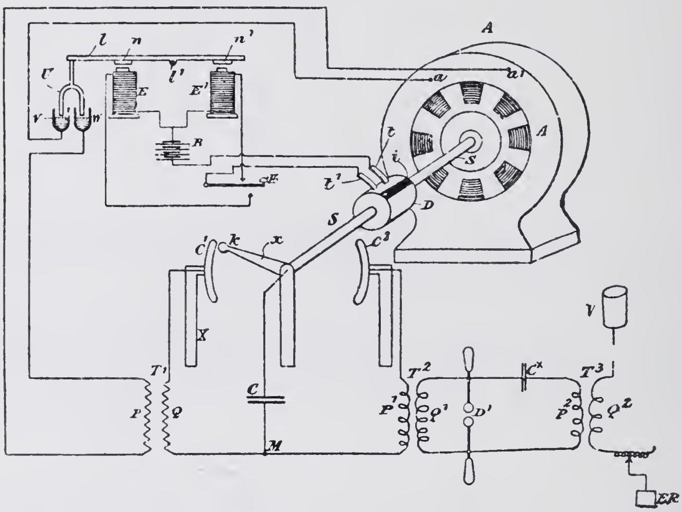


Fig. 62.—Rotating Arm Alternator and Transformer Plant for the Production of Powerful Electric Waves. (Fleming.)

at the end of the arm coming into close proximity to, but not touching, the curved sectors. An alternating current transformer, T_1, has its primary circuit, P, connected through a switch with the terminals of the alternator A, and its secondary circuit, Q, is connected by one terminal with the curved sector C_1, and the other to one surface of a large condenser, C, the corresponding surface of this condenser being connected to the central point of the revolving arm. The other curved sector, C_1, is connected to one end of the primary circuit of an oscillation transformer, T_2, the other end being joined to the condenser. The secondary circuit of this oscillation transformer is connected to a pair of spark balls. These spark balls are shunted by a second condenser, and the primary circuit to a third oscillation transformer, T_3. This last oscillation transformer has its secondary circuit connected in between an aerial wire, V, and an earth plate. The rotating arm X on the shaft of the alternator is fixed in such a position that just when

it comes to within touch of the curved sector C_1 the electromotive force of the alternator has its maximum value during one period. Hence if the transformer T_1 is a high tension transformer, under these circumstances a spark will jump across between the curved sector C_1 and the rotating arm X, and the condenser C will become charged. When the arm swings round into proximity with the other curved sector C_2, this condenser discharges itself through the primary circuit of the oscillation transformer T_2. The resulting oscillations charge the second condenser C′, and this in turn discharges across the spark balls with oscillations when its potential reaches a value corresponding with the length of the spark gap. Finally, oscillations are set up in the open circuit, and their energy radiated as electric waves. Signals are made by opening and closing the primary circuit of the alternating current transformer T_1. The purpose of the insulated cylinder on the shaft of the alternator is to prevent this opening and closing of the high tension transformer circuit during the time that the revolving arm is passing in front of the curved sectors. These curved sectors are such a length that the passage of the knob of the revolving arm over the sector is only a short fraction of the whole time of one half period of the alternating current, and takes place during the time that the electromotive force of the alternator is a maximum during the period.

The object of the insulating cylinder on the alternator shaft is to render it impossible to interrupt the charging of the condenser during the time the revolving arm is passing on its surface two curved plates of metal like an ordinary split tube commutator. Against this cylinder two metallic springs press, and these are therefore put into electrical connection when the springs are both touched by a metal part, but are disconnected when both are resting on an insulating portion of the cylinder. These springs are in series with a battery, key, and electromagnet. This electromagnet operates a mercury or other contact key, which opens and closes the primary circuit of the high tension transformer. The cylinder is so set on the shaft of the alternator that the operator, by pressing the hand key K, can tilt backwards or forwards the main key U. This last key, however, cannot be moved during the time of passage of the arm x in front of the sectors, but only during the remainder of a revolution of the arm. The locking of the main key in this manner is required to prevent the possibility of damage to the high tension transformer or condenser by suddenly interrupting a large current when it is flowing into the condenser. The performance of the plant is as follows: At each revolution of the alternator, which may occupy 0·05 of a second (corresponding to 1200 revolutions per minute), the first condenser is charged and discharged with oscillations. As this condenser is one of large capacity, say 1 mfd., these oscillations are, relatively speaking, slow. They may have a frequency as low as 100,000, or less. These oscillations are very slightly damped, as the spark resistance in the discharge circuit is very small and the circuit is non-radiative. At each of these oscillations the second condenser is charged, and as the capacity of this last condenser is much less than that of the primary condenser, its oscillations through its own spark gap and the primary of the oscillation transformer T_3, have a much higher frequency.

To secure the best result, however, the circuit composed of the condenser C′, the primary of the transformer T_3, and the secondary of the transformer T_2, must be tuned by the insertion of inductance, so as to have the same time period as the discharge circuit of the main condenser C. The spark balls D′ can then be set at such a distance apart that the voltage on the secondary terminals of the transformer T_2 cannot *per se* make a discharge across the gap, but the discharge is only brought about when resonance has so exalted the potential difference of the condenser C′ that it is able to discharge across the gap with oscillations. Hence we have a discharge of the condenser C′ taking place, not at every oscillation of the condenser C, but at every few oscillations. Nevertheless, the result is that the groups of oscillations resulting in the aerial circuit are far more numerous and of far greater amplitude than those taking place in the main con-

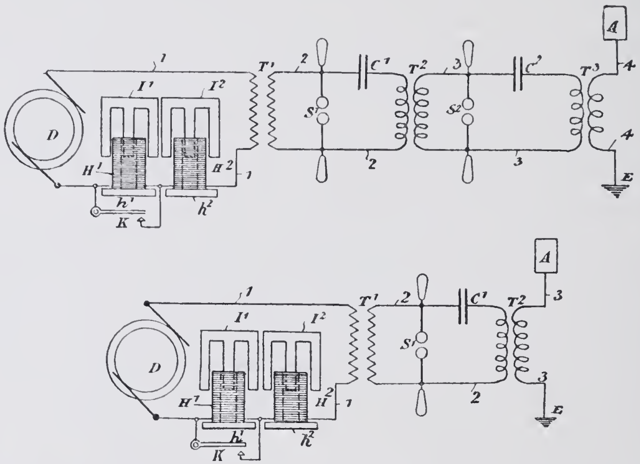


Fig. 63.—Alternator Transformer and Condenser Plant with Multiple Oscillation Transformers and Spark Gaps for the Production of Powerful Electric Waves. (Fleming.)

denser circuit. We are thus able to step-up the potential, and to step-up the group frequency and also the frequency of the individual oscillations in the groups, and obtain a very energetic radiation consisting of wave trains extremely close together.

Similar arrangements can be carried into effect employing a high tension continuous current dynamo.

In a subsequent specification, No. 3481 of February 18, 1901, the author described a simpler and yet more powerful arrangement for generating energetic electromagnetic waves.[40] In this arrangement a high tension alternator, A (see Fig. 63), has its terminals connected to the primary circuit of one or more alternating current transformers, T_1, which may be arranged with their primary circuits in parallel or series. It is usually most convenient to employ an alternator having an electromotive force of 2000 volts, and to employ a battery of high

[40] The equivalent United States Patent is No. 758,004, applied for April 8, 1901, dated April 19, 1904.

tension transformers raising voltage from 2000 to 30,000 volts. The primaries of these transformers may be joined in parallel on the alternator terminals, and the secondary circuits may be joined in series, so as to add together the potentials of the transformers. In the circuit with the alternator and the transformers are placed two coils of high inductance, H_1, H_2, which are provided with E-shaped iron cores, capable of being lowered down into these bobbins, so as to increase their inductance. One of these bobbins is short-circuited by a key, K. The secondary terminals of the alternating current transformer T_1 are connected to a spark discharger, S_1, the balls of which are shunted by a condenser, C_1, and the primary circuit of an oscillation transformer, T_2. A similar inductive coupling is then repeated with another condenser, C_2, spark ball, S_2, and oscillation transformer, T_3. The secondary circuit of this last transformer is finally connected to an aerial, A, and an earth plate, E. The operation of the arrangement is as follows: One of the choking coils, H_1, is short-circuited by the key K, and the iron core I_2 of the other choking coil H_2 is lowered into such a position that its impedance permits not more than the maximum full load primary current to flow into the transformer T_1 when the balls S_1 are short-circuited. The iron core I_1 of the choking coil H_1 is then lowered down into the coil, and if the key K is then raised the impedance of the choking coil H_1 will stop all current from flowing into the transformer T_1. When these arrangements have been made, the balls S_1 are set up such a distance apart that an alternating arc discharge will not take place, due to the mere secondary electromotive force of the transformer T_1 working alone without the condenser shunt circuit. The spark gap is thus made greater than that corresponding to the normal maximum voltage of the high tension transformer working alone. If, then, the condenser C_1 and oscillation transformer T_2 are connected to the spark balls S_2, as shown in the drawing, and the other connections also completed, we have three circuits inductively connected with one another. In the first place, there is the circuit of the alternator and the primary of the high tension transformer T_1. In this circuit we have an alternating current flowing, the frequency of which is determined by the speed and construction of the alternator. It is possible to arrange the inductance and capacity of the circuit composed of the condenser C_1, the primary circuit of the oscillation transformer T_2, and the secondary circuit of the high tension transformer T_1, that this circuit is in resonance with the alternator circuit. When this is the case, the alternator current will create a powerful secondary current in the condenser circuit, and the potential between the spark balls S_1 will accumulate to such a value that a discharge takes place across the spark balls. The condenser C_1 then discharges with oscillations, and these oscillations are transformed up in potential by the oscillation transformer T_2, and set up secondary oscillations and discharges in the circuit composed of the condenser C_2, the spark ball S_2, and the primary of the oscillation transformer T_3. Finally, these give rise to powerful high frequency oscillations in the aerial circuit, which throw off their energy in the form of electric waves. This result, however, is only secured when the several circuits thus inductively coupled are in resonance with each other.

The whole of the discharges are under perfect control by means of the key K, and when this key is up the impedance of the choking coil H_1 prevents any sensible current from flowing through the transformer T_1. When the key is down the oscillatory discharges succeed one another with great rapidity, hence they can be cut up into dots and dashes in accordance with the Morse code. The same specification provides numerous details of the construction of these transformers, and also of the condensers employed.

It is desirable that the condensers be arranged in parallel between two conductors, so that for each component condenser of the battery of condensers the length of circuit through which the discharge takes place is exactly the same. This arrangement is an exceedingly powerful arrangement for producing rapid trains of electric waves by multiple transformation of electric oscillations in circuits which are brought into resonance with each other.

In a British patent specification (No. 20,576, of November 14, 1900) the Author described another method of controlling the oscillatory discharges so as to cut them up into signals by means of a

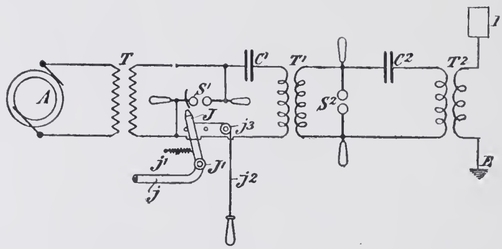


Fig. 64.—Method of Signalling by adjustable Air Blasts impinging on the Spark Balls. (Fleming.)

movable or directed air blast, as shown in Fig. 64.[41] A tube, J, from which an air blast is proceeding, is hinged so that the air blast can be directed between the spark balls, across which a condenser is discharging. These balls are set at such a distance apart that when the air blast is not directed on them the high tension transformer T creates an alternating current arc between the balls S_1, but no oscillations take place in the condenser circuit shunted across the balls. On directing the blast against the spark balls, the alternating current arc is blown out and an oscillatory discharge takes place.

By interrupting the air blast either by a valve in the pipe or by moving the nozzle, the oscillatory discharge can be created for long or short periods, as required, to make the signals of the Morse alphabet.

In another British patent specification (No. 22,126, of December 5, 1900) the Author described a similar multiple oscillation circuit, but the control of the oscillations was achieved by inserting in the circuit of the alternator and first transformer another regulating transformer, the secondary circuit of this regulating transformer being closed on

[41] The equivalent United States patent is No. 758,005, applied for April 8, 1901, and dated April 19, 1904.

water resistances, W_1, W_2, consisting of plates immersed in vessels of water. As long as the secondary circuit of this regulating transformer is open, its primary circuit offers such impedance to the flow of the current from the alternator, that no current passes through the primary circuit of the high tension transformer T sufficient in magnitude to charge the condensers connected with the secondary circuit of this last transformer. If, however, a key, K, in the secondary circuit of the regulating transformer is closed, then current at once flows through the high tension transformer T sufficient to charge the condenser C and create the oscillatory discharges.

It will be seen that the devices described in the above three mentioned British specifications, Nos. 20,576 and 22,126 of 1900, and 3481 of 1901, amongst other things, are for means of controlling the current flowing through the primary circuit of the battery of high tension transformers without at any time opening the said primary circuit.

Another arrangement of the said type described by the author in his British patent specification, No. 24,825 of 1901, is for an arrangement in which oscillations of different frequency can be created simultaneously in two aerials associated with one and the same oscillatory circuit actuated by some high tension transformer and alternator. In this manner two sets of waves of different wave length can be radiated simultaneously, sending different messages and received upon different receivers at the same or different places.

Another invention of the author in connection with transmitting apparatus is for a discharger (see British specification, No. 25,383, of November 20, 1903, or United States patent, No. 792,014), consisting of balls which are set in revolution by electric motors or other means, and included in a chamber in which nitrogen or carbonic acid gas is compressed.

The balls or discs between which the discharge takes place are driven round at a slow pace by means of gearing, which in turn is driven by a small electric motor or clockwork (see Fig. 65). When electric motors are employed, each ball or disc is preferably driven by its own motor, and these motors are contained in a cast or wrought iron sound-proof chamber, which also contains the ball discharger. As the contact surfaces are continually being changed they wear more evenly, and the kind of spark, therefore, required for the performance of electric wave telegraphy is better preserved. If these balls or discs are hollow, water may be caused to circulate through them and so keep them cool. It is found that a very great advantage is secured by using a short spark taken in compressed nitrogen enclosed in a strong iron reservoir, as the electric discharge can be made perfectly noiseless, and the unpleasant effects arising from this sound are obviated. In order to make the contact between the revolving ball or disc and the external electrical generator (whether it be a transformer, induction coil, or any other means), mercury cup contacts are used. The shaft carrying the ball or disc has on it a copper cup containing mercury, and a stout copper pin connected with the external circuit dips into this mercury. The disc can, therefore, revolve, and yet a good connection is kept up with the external circuit. Otherwise the mercury cups are connected with the external

circuit, and a copper disc or pin on the revolving shaft which carries the balls dips into the mercury in this fixed cup.

If the discharger is enclosed in an air-tight reservoir containing compressed gases, then the rods or cables coming from the generator must pass air-tight through the sides of the reservoir by means of glands. The screws also serving to alter the distance of the balls or discs must in the same way pass air-tight through the sides of the reservoir.

In Fig. 65 a is a cast-iron ball, say about 6 inches in diameter, which is traversed by a copper shaft, b, having a hard steel point, b', on the bottom end, and the top end having in it a steel pin, b^2, entering the cup formed in the top of the ball. Each ball is supported upon a

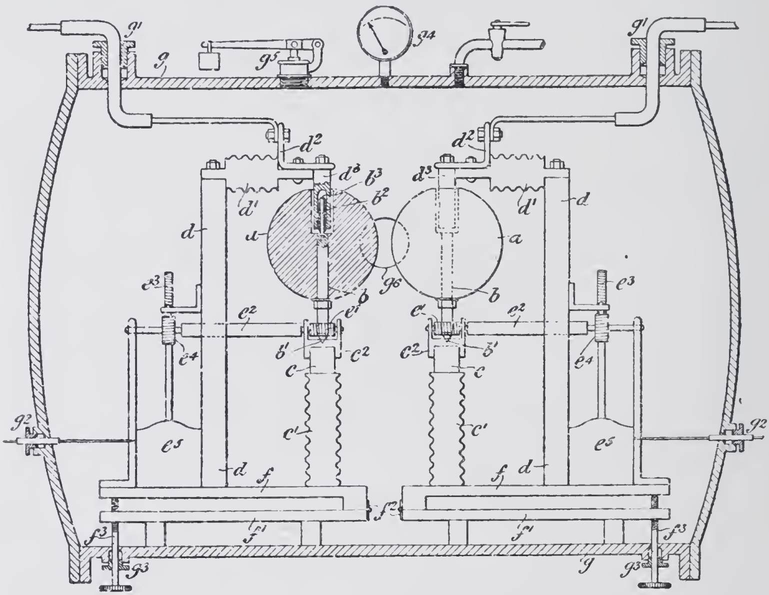


Fig. 65.—Rotating Ball Discharger Working in Compressed Nitrogen. (Fleming.) a, a, rotating spark balls; e^5, electric motors; f, f, tilting tables for varying spark length; g^1, g^1, discharge circuit leads.

wooden bridge, c, on ebonite insulators, c', carrying a brass sole plate, c^2, in which there is a recess for the steel point b' to rest. The ball is sustained in an upright position in the following manner: d, d are two stout wooden uprights, which carry horizontal corrugated ebonite insulators, d'. These ebonite insulators carry a transverse copper strip, d^2, having attached it to a copper pin, d^3. This copper pin has a longitudinal hole bored in it to receive the steel pin b^2, and in order to prevent metal to metal contact, a glass tube, b^3, is slipped over the pin b^2. The cup in the top of the ball is then filled with mercury. In this manner the ball is connected electrically by a very good joint with the copper strip d^2, which is the terminal of the instrument, and yet the ball itself is free to revolve quite easily. The ball is driven round by an electric motor in the following way: On the lower end

of the shaft b is fixed a worm wheel, e, which engages with a worm, e', on an insulated shaft, e^2, of ebonite. On the shaft e^2 is a second worm wheel, e^3, driven by the worm e on the shaft of the motor e^5. The whole arrangement is carried upon a platform composed of two boards, f, f', jointed together by hinges, f^2. The upper board f can be tilted by screw f^3, so that by tilting the two tables which carry the two halves respectively of the discharger, the balls can be brought nearer to or moved away from one another, so as to vary the spark gap.

This apparatus is enclosed in a sheet-steel or cast-iron drum, g, sufficiently large to contain the whole discharger conveniently, preferably constructed like a small cylindrical boiler.

In this boiler there is a pair of glands or stuffing boxes, g', through which the cables are brought air-tight to the copper strip d^2, and also two glands, g^2, for the cables, conveying the current and driving the small motors e^5. Stuffing boxes, g^3, are also provided for the screws f^3. In this manner the balls can be driven round in an air-tight chamber into which nitrogen or carbonic acid can be pumped under pressure.

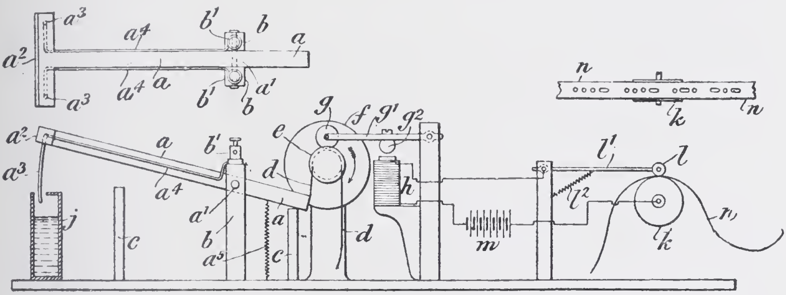


Fig. 66.—Automatic Signalling Key for High Tension Alternator Circuit operated by Punched Tape. (Fleming.)

As the action of the electric spark is to combine together the oxygen and nitrogen of the air producing nitric acid, it is better to employ nitrogen instead of air.

It is desirable, therefore, to provide the closed chamber with a pressure gauge, g^4, and a safety valve, g^5, so that a stated pressure may not be exceeded. In this closed chamber or iron boiler there should also be a small peep hole, g^6, closed with a stout glass plate to enable the spark to be inspected.

Another of the Author's devices is a signalling key operated by a punched tape (see British specification, No. 25,382, of November 20, 1903, or United States specification, No. 792,015). The object of this invention is to actuate the key employed to short-circuit the choking coils described in the transmitting arrangement covered by the British specification, No. 3481 of 1901. For this purpose a key is used which effects the required short-circuiting by immersing in a mercury vessel two prongs carried on the end of an arm (see Fig. 66). A light wooden arm, a, is pivoted on a fixed stand, and carries two wires, which are connected respectively to two fixed terminals. These wires end in curved branches, which are immersed

in a vessel of mercury, *j*, when the arm is depressed, thus connecting or short-circuiting the choking coil terminals. The switch terminals are connected by wires with the choking coil H in the arrangement above mentioned. The movement of the arm is effected in the following manner: The shorter end of the arm carries a tape, *d*, which lies over the pulley of a rapidly revolving electric motor. A jockey pulley, *g*, rests upon this tape, the said jockey pulley being carried at the end of a pivoted arm, to which is also attached an iron armature situated near the poles of an electromagnet, *h*. When the circuit of this electromagnet is closed, the armature is drawn down, and the jockey pulley presses the tape against the pulley of the revolving motor, causing it to grip and be wound up as far as it will go. The short end of the arm is then raised, and the long side depressed, thus immersing the curved wires in the mercury vessel.

The electromagnet is energized by means of another battery, the circuit of which is closed through two wheels. One of these is a wide pulley, on which the perforated paper tape, *n*, is made to travel by means of clockwork, and the other wheel is a small platinum disc, *l*, which drops through the holes punched in the paper tape and makes contact with the larger wheel, thus completing the magnet circuit at intervals and for times corresponding to the holes punched in the tape in accordance with the Morse signals. This arrangement permits of the rapid and certain operation of the key, the function of which is to short-circuit the choking coils in the arrangement described in Fig. 63, and so create the oscillations in the multiple transformer circuit. Any message can be punched in section lengths of paper tape, and these fed through the transmitter in proper order. In transmitting code messages, this automatic sending key is of great value, as the spacing of letters and words is accurately kept, whatever the speed of transmission.

The author's inventions in connection with the measurement of long electric waves and the conversion of electric oscillations into continuous currents by means of an *oscillation valve* have already been described in Chap. VI.

17. Electric Wave Wireless Telegraphy in the United States.—Practical work in wireless telegraphy by electromagnetic waves in the United States is mainly connected with the names of R. A. Fessenden, Lee de Forest, J. S. Stone, and a few others, although most valuable work has been done by purely scientific investigators such as Professor G. W. Pierce.

The record of this work is chiefly to be found in the bulky volumes of United States patent specifications. These documents are often elaborate treatises on the subject, abounding in references to the literature and present "state of the art."

It is a matter of the greatest difficulty in reading these specifications to separate out the wheat from the chaff and distinguish that which is really new and useful from that which is simply an effort to disguise old knowledge in a new form.

For the purposes of this treatise, it will be sufficient to mention the principal specifications of the chief workers, with a few words of comment describing their contents, and leave the reader to make

further acquaintance with them if desired, in the volumes in the Patent Office Library.

18. Work of R. A. Fessenden.—The extensive and practical work of Professor R. A. Fessenden on wireless telegraphy commenced in connection with the United States Weather Bureau at Washington, and continued in connection with the National Electric Signalling Company of U.S.A., has been directed to the invention of wave detectors, appliances for producing continuous trains of electromagnetic waves, methods for increasing wave energy and wave length, and devices for achieving the isolation or syntonization of wireless telegraph stations and methods of conducting wireless telephony.

The following list of United States patents granted to him includes those in which his chief contributions to the subject are specified.

No. 706,735 and No. 706,736, applied for December 15, 1899.—These specifications cover a dynamometer detector for electric waves. Starting from the fact discovered by the author of this treatise in 1887, that a ring or disc hung at an angle of 45° to the plane of fixed coils is caused to deflect when an alternating current passes through the coils, Fessenden applied this principle in the construction of a device for detecting electrical oscillations. A light suspended silver ring with attached mirror is placed obliquely between two fixed coils, which last are in the circuit of the receiving aerial. The oscillations set up in the aerial, and therefore in the fixed coils, create induced currents in the ring and cause it to deflect. This form of receiver, is useful in metrical work as shown by Professor G. W. Pierce, but is not sensitive enough for long-distance practical wireless telegraphy.

These specifications also include diagrams and descriptions of a transmitting arrangement consisting of a Marconi aerial wire, spark balls, and earth connection, but a condenser shunted across the spark gap to maintain sustained radiation. It is stated that the shunt circuit must be tuned to the receiving conductor otherwise the oscillations produced by it will have no action on the wave responsive device at the receiving circuit. It was subsequently asserted by the patentee that the sixth claim of No. 706,735 and the twenty-sixth claim of 706,736 covered the invention of the local oscillatory circuit and an antenna tuned to it (see *The Electrician*, February 15, 1907, Vol. 58, p. 675, 1907).

No. 777,014, applied for June 2, 1900.—This contains a description of an elaborate apparatus for generating two or more series of electric waves, and recording at each receiving station only such series of waves as are sent out in a particular order. Its purpose is to obtain privacy in the telegraphy. With this object he employs several sending and receiving aerials, and the apparatus is so arranged that to produce a telegraphic *dot* or *dash* at the receiving station requires the conjoint action of waves from all the sending wires, and these are caused to perforate at the receiving station telegraphic paper, which then passes through a recording apparatus. This last records a dot or dash only when certain properly spaced perforations are made on the telegraphic tape by the conjoint action of the group of waves sent out from the transmitter. The apparatus in principle somewhat resembles that developed later by Anders Bull.

No. 706,737, applied for May 29, 1901.[42]—This is a patent for the construction of an aerial consisting of a number of wires, grouped in cylinder fashion, to construct an aerial of large capacity. The patentee points out that if such an aerial is associated with an inductance and a high frequency alternator directly, the

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[42] The equivalent British specification is No. 17,708, of August 12, 1902.

alternator having one terminal to the aerial and the other earthed, no spark gap being used, it would radiate very long electric waves. Two reissues Nos. 12,168 and 12,169 were applied for on October 20, 1903. This specification, however, is chiefly important in that the patentee clearly describes the necessary characteristics of a high frequency alternator for radiotelegraphic work.

No. 706,738, applied for May 29, 1901.—This covers various forms of sending and receiving aerial of large capacity.

No. 706,739, applied for May 29, 1901.[43]—This patent covers devices for clothing or surrounding the sending aerial with media, having large dielectric constant and considerable permeability. The patentee desired to create long electric waves with short aerials, and he considers that he can do it by packing round the aerial with dielectrics such as paraffin, pitch, indiarubber, or other dielectrics having iron filings embedded in it. The author is not aware that the process has been tried, and in any case it would probably result in considerable absorption of the energy of the oscillations. The suggestion is based upon the optical fact that when a wave of light emerges from a material of high refractive index into one of smaller, the wave length is increased proportionately to the velocity, since the frequency must remain the same.

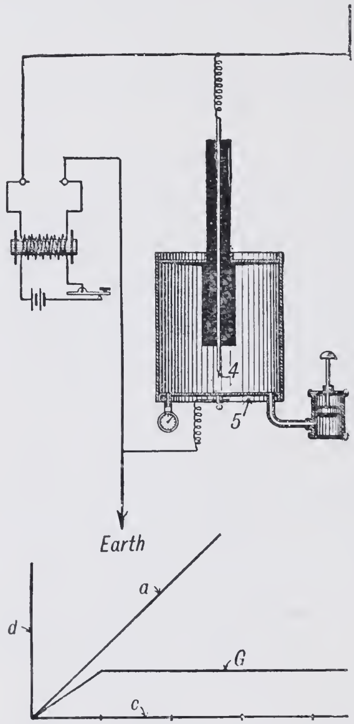


FIG. 67.—Fessenden's Spark Discharger using Compressed Air.

No. 706,740, applied for September 28, 1901.[44]—This is for a system of electric wave telegraphy in which two or more radiators are employed to send out persistent or undamped waves of different wave length, and at the receiving station a corresponding number of receiving aerials are employed, and a receiver which cannot operate except in virtue of the conjoint action of all these waves of different wave length. The coherer or cymoscope placed in the receiving aerial circuit is not acted upon by either wave train separately, but only by the sum or difference of their actions on the receiving aerials.

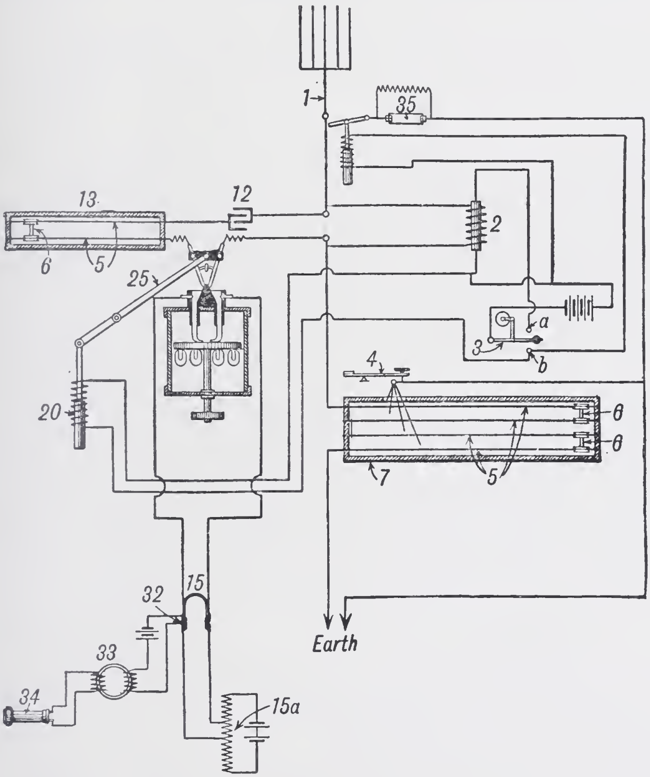
No. 706,741, applied for November 5, 1901.—This specification covers devices for creating the oscillatory spark in the wave-generating circuit in the interior of a vessel in which air or other gases is compressed. The inventor prefers to take the spark discharge between a plate, 5, and a point, 4 (see Fig. 67). He states that the terminals are to be adjusted about 0·26 inch apart, and that as the pressure of the gas increases the dielectric strength is raised to almost any extent without material loss in oscillatory power, whereas in air at ordinary pressure increasing the voltage beyond that sufficient to give a 1-inch spark in air results in no increase in radiation. He also states that if we employ a constant spark voltage and raise the gas pressure, then the corresponding spark length is reduced as the pressure rises, but that up to fifty pounds pressure on the square inch no marked increase in the electric radiation takes place. If, however, the pressure is increased beyond sixty pounds, the patentee states that the radiation begins to increase, and at eighty pounds is about three and a half times that at fifty pounds, and becomes, moreover, substantially proportional to the potential of the source of supply. This result may be brought about by the much greater

[43] The equivalent British patent is No. 17,703, of August 12, 1902. The reader may compare this specification of Fessenden's with those of J. S. Stone, Nos. 717,511 and 717,512, applied for January 23, 1901.

[44] The equivalent British patent is No. 17,704, of August 12, 1902.

suddenness with which the highly compressed gas yields under electric stress when the disruptive voltage is reached.

No. 706,742, applied for June 6, 1902.[45]—In this specification the patentee describes the complete arrangement of transmitter and receiver for utilizing the thermal receiver already described, constructed with a fine platinum wire in a vacuous bulb. The transmitting arrangement consists of a multiple aerial, 1 (see Fig. 68), having the spark balls at its base connected to the secondary terminals



From "The Electrician."

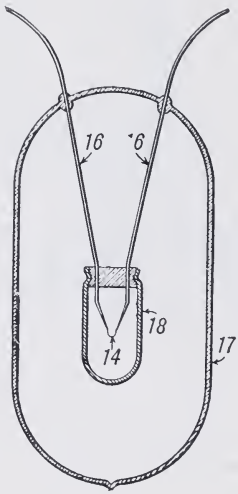
Fig. 68.—Diagram of Connections in Fessenden's Receiving Apparatus for Electric Wave Telegraphy.

of an induction coil. The lower spark ball is connected to the earth through an adjustable inductance consisting of parallel wires placed in a vessel of oil, the effective length of these wires being variable. The receiving arrangement consists of a circuit including a condenser, 12, and a variable inductance, 13, and also one of the wire barretters or thermal receivers already described (see Chap. IV.; see also Fig. 69). As these fine loops of wire are easily destroyed by any excessive oscillations, an arrangement is provided by which a new loop can be

[45] The equivalent British patent is No. 17,705, of August 12, 1902.

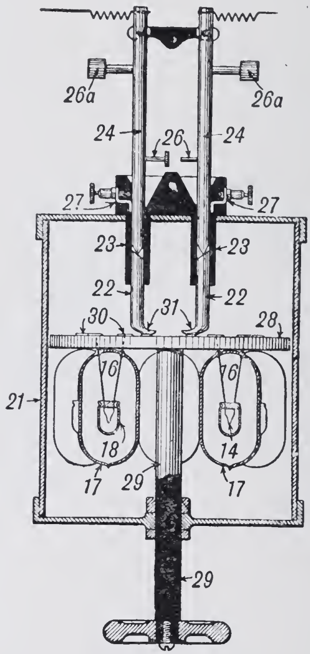
quickly substituted for a burnt-out one (see Fig. 70). The thermal detector is connected in between the aerial and the earth when it is desired to receive. The effect of the electric waves impinging on the receiving aerial is to create oscillations which heat the very fine wire of the barretter and increase its resistance.

To detect this increase in resistance, the barretter is also joined into a circuit which includes a telephone and a shunted voltaic cell. When the resistance of the barretter is suddenly increased by the rise in temperature, the current through the telephone is suddenly



From "The Electrician."

FIG. 69.—Fessenden Hot-wire Receiver or Barretter, consisting of a fine loop of platinum wire (14) enclosed in a bulb (18).



From "The Electrician."

FIG. 70.—Fessenden's Arrangement for working Barretters in Parallel or making Changes.

varied, and a sound is heard, long or short, according to the duration of the wave trains, thus signalling a *dash* or *dot* on the Morse code.

The same specification contains elaborate instruction for making the fine platinum wire loops and mounting them in bulbs to make the barretter; also descriptions of the keys and sliding inductances employed.

In this specification No. 706,742 Fessenden describes a method of producing oscillations in the antenna by means of continuous currents. A continuous current dynamo has its terminals connected to the balls of a spark gap, which balls are also connected respectively to an antenna and to the earth and also shunted by a condenser and inductance. A variable resistance is interposed between the spark

balls and the dynamo. It is asserted that by proper adjustment of the resistance an intermittent discharge may be obtained between the balls.

This method was subsequently described by the patentee as a method of producing oscillations in the antenna by means of an electric arc and claimed as an improvement on Elihu Thomson's method of producing sustained oscillations although no proof is given in the specification that either method did actually succeed in producing true persistent and undamped oscillations (see *The Electrician*, Vol. 58, p. 676, 1907).

No. 706,743, applied for June 26, 1902.—This describes a method of recording the signals given by a hot-wire barretter on a photographic paper band and developing the same.

No. 706, 744, applied for June 6, 1902.—Gives further details of the process of making the platinum wire barretter or thermal receiver. Since one single loop is very fragile, a number of such barretters may be joined in parallel. This does not decrease the sensitiveness of the receiver as a whole, since the reduction of resistance is accompanied by a reduction in inductance of the whole of the loops taken together, and hence a greatly increased oscillation current results, which causes the percentage change in resistance to be about the same for many as for one single loop.

No. 706,745, applied for July 1, 1902.—This specification covers a description of a number of receiving devices and the best mode of employing them, and distinguishes between those modes which are useful when using potential actuated devices, such as a coherer, and those when using current actuated devices, such as a thermal cymoscope. The patentee draws a comparison between the sensibility of a coherer and his thermal receiver, stating that with the latter messages at the rate of thirty words per minute were sent and received over a distance of fifty miles, using a spark at the sending end 0·03 inch in length, whereas with the same arrangement he says a spark 5½ inches had to be employed when using a coherer. This, however, only shows that under the circumstances of the comparison the coherer was being used in a very disadvantageous manner, and the comparison is not an equitable one.

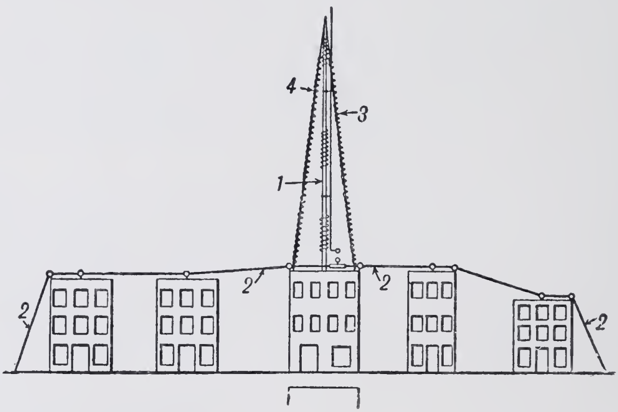
No. 707,746, applied for July 1, 1902.[46]—The patentee describes in this document an arrangement which he calls a wave chute (see Fig. 71). This appears to consist of an extensive wire netting, which is connected to the earth plate at the base of the aerial, and spreads over any buildings which may be in its neighbourhood.

No. 715,043, applied for August 27, 1902.[47]—This specification covers the description of a form of magnetic cymoscope or wave detector. A ring-shaped core of iron wires is wound over with two circuits, and these circuits are connected to a two-phase alternator so as to produce a rotating field in the interior of the core. We may regard this rotating field as produced by the slow movement round the ring of a series of magnetic poles. Owing to the hysteresis of the iron, the induction in the core lags behind the magnetizing force. The ring is wound over in addition with a solenodial winding which is in connection through an air core transformer with the receiving aerial. When oscillations are set up in the aerial by the impact of

[46] The equivalent British patent is No. 17,703, of August 12, 1902.
[47] The equivalent British specification is No. 26,553, of December 2, 1902.

electric waves, the induced oscillations travel round the iron, annul its hysteresis, and the induction in the core makes a sudden movement up into step with the magnetic force. The interior of the ring is surrounded by two coils at right angles to one another, which are connected with the windings of a magnetic telephone, small condensers being interposed. The slow movement of the flux travelling round the space does not therefore affect the telephone, but any sudden movement due to oscillations occurring in the demagnetizing coil causes a sound in the telephone, hence the arrangement serves to detect oscillations in the aerial, and therefore waves falling upon it.

No. 727,331, reissue No. 12,115, application for reissue filed May 5, 1903.—This specification relates to the "liquid barretter" or wave responsive device of the type claimed in U.S.A. patent, No. 706, 744. Fessenden found that if a very thin wire of platinum was placed in an electrolyte such as nitric acid, and if the wire was broken in the middle, it acted as a wave responsive device. He was thus led to



From "The Electrician."

FIG. 71.—Fessenden's Wave Chute.

the invention of what is now called the electrolytic detector in which a metal plate and a short length of very fine wire are immersed in an electrolyte, and when this electrolytic cell is placed in series with a small continuous voltage and a current detector such as a telephone it becomes responsive to feeble electric oscillations as described in Chap. VI. This patent was upheld by Judge Wheeler in the U.S.A. Circuit Court of the Southern district of New York when sued upon by the National Electric Signalling Company *v.* the De Forest Wireless Telegraph Company in 1905.

No. 730,753, applied for April 9, 1903.—This specification relates to improvements in the apparatus described in the United States patents, Nos. 706,735, 706,736, 706,737, 706,747, and 727,325. It has reference to methods for producing continuous trains of electric waves by means of alternators or continuous current dynamos. In the particular arrangement described in this specification, the patentee proposes to pass the current from a continuous current dynamo through a high resistance, and to charge by means of it some condenser to a sparking potential. Since the condenser takes time to charge through the resistance, it rises up to

a certain potential and then discharges again. The discharge of the condenser sets up oscillations in an associated aerial wire. The patentee takes pains to prove that this arrangement was not anticipated in the United States patent, No. 550,630, granted to Elihu Thomson.

No. 731,029, applied for May 4, 1903.—This specification covers forms of liquid barretter, of the type previously described in the United States patent, No. 706,744, granted to R. A. Fessenden, August 12, 1902. The patentee describes five or six methods for constructing a liquid resistance which changes its resistance under the action of electric oscillations. He finds that a liquid, such as dilute sulphuric acid, is preferable to a fine wire made of platinum, since the change in resistance of platinum is only about 0·33 per cent. per degree Centigrade, whereas the change in resistance of the dilute sulphuric acid may be as much as 12 per cent. per degree Centigrade. He gives several methods for forming a *liquid barretter*, to which reference has already been made. The one to which preference is given consists of a very fine platinum wire immersed to a small depth in nitric acid, the thin platinum wire being prepared by the Wollaston process, and the silver dissolved off to the required extent by immersing the compound wire in the nitric acid.

As has already been pointed out, the action of this liquid barretter, which Fessenden asserts is due to a thermal action, may be explained as due to an annulment of the electrolytic polarization by the electric oscillations.

No. 12,115, reissued letters patent, corresponding to No. 727,331, dated May 5, 1903.—This is a reissued United States patent which refers to the above-described liquid barretter.

No. 752,894, applied for December 29, 1902.—In this specification the patentee describes a form of receiving arrangement which is not affected by individual oscillations, but only by groups of oscillations, with the object of obtaining an arrangement insensitive to stray or undesirable waves, but only affected by groups of waves sent out at regular intervals from a station intended to be in syntony with that particular receiver. Very much the same device had previously been described by Blondel.

No. 752,895, applied for March 14, 1903.—This specification describes a method of preventing interference by external disturbances by the use of an auxiliary or neutralizing antenna, such that the effect of the waves it is not desired to receive is annuled by their counter-action upon the two antennæ, but the waves it is desired to absorb do not so affect both antennæ.

No. 753,863, applied for September 28, 1901.—This is one of the earliest specifications for wireless telephony. The patentee proposes to employ undamped or nearly unintermittent traces of oscillations and to modulate their amplitude by means of a microphone and so radiate from an antenna waves which represent in amplitude the wave form of speech. These are to be received by another antenna and made to affect a telephone receiver. Fessenden had at this date clearly enunciated the essential principles of radiotelephony.

No. 753,864, applied for October 1, 1903.—This is for a horizontally extending antenna, but nothing is said about its directive quality.

No. 754,058, applied for August 8, 1903.—This is for a high speed turbine-driven alternator for producing high frequency undamped oscillations. He refers to a high frequency alternator in his U.S.A. patent No. 706,737, which he says gave a frequency of 20,000 and had an efficiency of 80 per cent.

No. 777,014, applied for June 2, 1900.—This specification contains a description of a method of isolating stations by sending groups of waves spaced in a certain manner. The receiver is only affected by the arrival of this special group of trains of waves, but not otherwise. The method has a similarity to that devised by Anders Bull.

No. 793,647, applied for December 14, 1904.—This is for improvements in capacities made with sections of insulated cable.

No. 793,648, applied for December 14, 1904.—A liquid barretter with compressed air, 40–50 lbs. per square inch, in the containing vessel, whereby the signals are said to be improved.

No. 793,649 and No. 793,750, applied for March 30, 1905.—These are specifications of Fessenden covering methods for radiotelephony.

No. 793,651, March 30, 1905.—A condenser for wireless telegraphy consisting of metal plates placed in a vessel containing air under great pressure, also for methods of constructing and supporting large antennæ.

No. 793,652, applied for April 6, 1905.—This specification describes means for sending and receiving messages simultaneously by connecting the antenna alternately to the sending and receiving circuits.

No. 793,718, applied for March 30, 1905.—The use of a water jet as an antenna.

No. 793,777, applied for March 30, 1905.—A detailed description of a condenser for radiotelegraphy consisting of metal plates in a vessel containing compressed air or gas.

No. 814,951, applied for December 14, 1904.—Condensers for radiotelegraphy made with sheets of metal gauze.

No. 897,278, applied for October 6, 1906.—This is one of Fessenden's specifications for improvements in methods for preventing interference. The signalling apparatus (receiver) comprises an inductive coupling and a receiver placed on the secondary circuit wholly enclosed in the primary circuit so that the primary shields it from disturbing influences.

No. 897,279, applied for December 17, 1906.—An arc method of producing undamped oscillations, the arc being contained in a vessel with gas at a high pressure.

No. 915,280, applied for February 8, 1907.—A vacuum tube receiver containing helium.

No. 916,428, applied for November 17, 1905.—An improved form of liquid barretter or electrolytic receiver.

No. 916,429, applied for July 8, 1903.—A receiver consisting of a jet of liquid.

No. 917,574, applied for March 26, 1907.—A receiver depending on the change in friction of surfaces in contact produced by electric oscillations passing through the contact.

No. 918,306, applied for July 1, 1907, and 918,307, applied for August 25, 1908. —Apparatus for producing high frequency groups of trains of electric waves. In these specifications Fessenden draws attention to the importance of employing with telephone methods of reception a group frequency in spark telegraphy which is of the order of 900 or 1000 per second. The result is to enable the ear to distinguish easily between the musical sound of the signal spark and the lower note or irregular grating sounds due to atmospheric discharges.

No. 923,962, applied for December 31, 1906.—Methods for sending and receiving simultaneously in the case of radiotelephony.

No. 923,963, applied for January 9, 1907.—Producing persistent oscillations by an electric arc formed in rare gases, Argon, Neon, etc.

The further references to some of the above mentioned specifications will be made in later chapters of this work. Fessenden has particularly devoted attention to the subject of radiotelephony, and many of his inventions, such as the high frequency alternator, have been directed to this end and are of considerable value.

Additional references to the work of Fessenden will be found in Chapters IX. and X., under the heading of Radiotelegraphic Stations and Radiotelephony.

19. Patents of Lee de Forest in connection with Wireless Telegraphy.—Another patentee who has been granted numerous patents in the United States and other countries for inventions connected with wireless telegraphy is Lee de Forest. We shall briefly abstract the subject-matter of his chief United States patent specifications, and refer to the contents of some of them elsewhere.

They cover detailed descriptions of various forms of electrolytic and magnetic wave detector, also devices proposed for affecting syntonic telegraphy, for determining the distance and location of sending stations, for various forms of aerials intended to secure immunity of a receiving circuit from influence by vagrant electric waves, and other appliances for practical working of wireless telegraph stations.

No. 716,203, applied for September 1, 1900.—This patent, granted to Lee de Forest and E. H. Smythe, is for a "variable resistance" material applicable as a wave detector, consisting of two metallic plates placed in a vessel containing a liquid. Water is stated to be "perfectly satisfactory" as the liquid, and the best results are said to be obtained when some porous material is interposed between the electrodes. The cell has its electrodes connected through two choking coils with a telephone and single voltaic cell, and, furthermore, one pole of the electrolytic cell is connected to earth and the other to an aerial. The electrodes in the cell should be close together, and may have unequal surfaces. It is stated that the action of electric oscillations on the cell is to *increase* its resistance. It is referred to in the specification as a "variable resistance conductor," altering in resistance under the action of electrical oscillations produced by electric waves falling on the aerial, but self-restoring. The sudden change in its resistance varies the current of the cell passing through the telephone, and hence creates an audible signal. The application of the arrangement as a receiver in wireless telegraphy involves the use of the Marconi aerial wire, earth connection, and choking coils. If it is a fact that the action of electric oscillations is to *increase* the resistance of such a cell, then it differs strikingly from other forms of electrolytic polarization cell, for in these last the action of electric oscillations reduces the effective resistance of the electrolyte by annulling in part or entirely the polarization of the electrodes, and so reducing the effective resistance of the cell.

No. 716,000, applied for July 5, 1901.—Contains a description of another form of variable resistance wave detector. A glass or ebonite tube has in it two plugs, one of which is capable of being advanced by a screw, so that the interspace between the two plugs can be made a small fraction of an inch. Between these electrodes is placed an electrolyte consisting of glycerine or oils, mixed with oxide of lead (litharge), and a small quantity of water or alcohol, mixed with metallic powders, preferably tin, silver, or nickel. Sometimes the ends of the plugs are made cup-shaped, and the cups filled with a mixture of oxide of lead and glycerine. This electrolytic cell is placed in series with a voltaic cell and a telephone or other telegraphic instrument, choking coils being interposed. The cell is also connected by one terminal to an aerial and the other to the earth. The operation of the battery current is to electrolyze the mixture, and form chains of metallic particles, while the action of an electric oscillation passing through the cell is to break up the chain of particles and so suddenly increase the resistance of the cell. Hence a listener at the telephone hears a sudden click of the telephone due to the decrease in the current passing through the cell, and as soon as the oscillations cease the chain of metallic particles is instantaneously reconstructed, and the resistance of the cell again falls. A train of electric waves falling on

the aerial produces, therefore, a continuous sound in the telephone, and audible singles can be made, equivalent to the dot and dash of the Morse alphabet.

No. 716,334, dated December 16, 1902.—This specification is merely a division of the previous specification applied for on July 5, 1901.

No. 720,568, applied for March 6, 1901.—This specification describes a form of duplex aerial consisting of two aerials of the Slaby type, having lateral connections at some point just above the ground. The ends of these two lateral wires are connected to the terminals of an electrolytic receiver. The length of the two lateral wires is so adjusted that the phases of potential at their open ends differs by 180 degrees.

The same specification also covers a description of a closed loop receiving aerial.

The advantage of the double aerial is stated to be that by rotating the system of antennæ round a vertical axis the variation in its sensibility enables the direction of the arriving wave front to be determined, and hence that of the radiant point.

On comparing this U.S.A. specification with that of J. S. Stone, No. 716,134, applied for January 23, 1901, it will be seen that the latter patentee had previously described a somewhat similar plan for locating the direction of the sending station by the use of double or looped aerials.

No. 730,246, applied for March 8, 1902.—This long specification, with fifty-three claims, includes a description of an application of the so-called Lecher wires as part of a receiving circuit. An aerial receiving wire is interrupted at some point near the ground and two lateral insulated wires inserted. These wires may be twisted together and contained in a box of oil. If the length of the wires is adjusted with reference to the frequency of the electric waves incident on the aerial, then stationary electric waves are set up in these wires with loops and nodes of potential at regular intervals. Any wave-detecting potential-actuated device, such as a coherer, can be placed across the two wires as a bridge at an antinode of potential, whilst any current-actuated device can be placed in the run of one of the wires at an antinode of current. The object of the arrangement is to construct a receiving aerial which will be insensitive to an aperiodic or solitary electric wave, but responsible to a train of electric waves having some definite assigned period.

No. 730,247, applied for November 4, 1902.—This is another specification covering a receiving aerial in which Lecher wires are employed, twisted together as a resonant system, sensitive only to waves of a certain definite period. A potential-actuated cymoscope is placed at the open end of the parallel wires at a potential loop, and also connected through choking coils and a single voltaic cell with a telephone as a detecting device.

No. 730,819, dated June 9, 1903.—This is a subdivision of the previous patent.

No. 749,131, dated January 5, 1904.—This is a division and a reissue of patent No. 720,568, applied for March 6, 1901, and refers to forms of antennæ intended to give direction to the radiation, and also to enable the direction of the radiant point to be determined. The radiator comprises two antennæ, one horizontal and one vertical, connected to spark balls, and the radiation is said to be concentrated in the plane of these antennæ.

No. 748,597, applied for December 24, 1902.—In this specification the patentee proposes to surround a single vertical sending aerial with a number of other aerials arranged on a parabolic line, of which the first aerial is in the focus. Each aerial may be provided with its own spark balls, the object of this arrangement being to act as a reflecting surface and direct a beam of radiation in any direction. In the absence of specific information as to performance, it is impossible to estimate the practical value of such a device.

No. 770,228, applied for December 24, 1902.—This patent is for a contact cymoscope consisting of steel and aluminium surfaces held lightly in contact with a spring. The patentee states that such an arrangement is self-decohering. It belongs to the type of microphonic receivers, which fall but slightly in resistance on the passage of an electric oscillation through the contact, and are therefore suitable for use with a telephone and local cell. If the pressure at the imperfect contact is light and properly adjusted, the cymoscope is self-restoring and requires no tapping.

No. 749,178, applied for March 5, 1903.—Contains a description of a Morse

signalling key with the contacts working under oil and under some circumstances, a magnetic blow-out being employed if necessary.

No. 750,216, applied for May 14, 1902.—This specification describes a number of arrangements of transmitting and receiving aerials for syntonic telegraphy, in which the Lecher conductors are employed as the resonant system.

No. 770,229, applied for March 14, 1902.—This specification covers arrangements for receiving aerials which are intended to be impregnable against the attacks of solitary waves or aperiodic electromagnetic disturbances, but easily influenced by periodic trains of electric waves of suitable period. Descriptions in this specification, however, do not give any sufficient proof of the actual and practical value of such arrangements.

No. 749,434, applied for June 4, 1903.—This specification contains a description of a combination of sending and receiving apparatus by which messages are to be sent and received simultaneously at the same station. A revolving commutator cuts the connection between the actual wave detector or cymoscope and the aerial at the moment when the spark happens. The patentee proposes to employ a wave detector which is not injured *per se* by strong impulses from a spark near by, such as a Rutherford magnetic detector or other self-restoring wave indicator.

No. 749,371, applied for June 4, 1903.—Comprises an application of a magnetic telegraphic wave detector, similar in principle to that of Marconi, to syntonic receiving apparatus, such that electric waves or impulses differing from those which the apparatus is designed to detect will not affect it.

His method is to construct a differential magnetic detector with two oppositely wound coils, one in connection with a simple aerial and the other in connection with an aerial with a resonant Lecher system of wires attached to it, so that it is syntonic. The idea is that irregular electromagnetic impulses will affect both aerials equally, and therefore produce no effect on the magnetic detector, whilst the syntonic trains of waves will chiefly affect one aerial alone.

No. 749,372, applied for June 4, 1903.—For a method of wireless telegraph signalling, based upon the radiation of a continuous series of high frequency electric waves having a spark frequency varied in a predetermined cycle, producing manifestations, and by means of them producing, at the receiving station, signals which vary in accordance with the variations of spark frequency.

No. 749,435, applied for June 17, 1903.—This is a specification claiming an arrangement for a wireless telegraph transmitting station, comprising a gas or oil engine, an alternator, a transformer, an extra high-tension transformer, two choking coils, condensers, an aerial wire, and earth connection. Precisely similar arrangements had been erected and employed by the Author of this treatise two or three years previously; power plant for creating electric waves involving the use of gas engines or oil engines, and high tension transformers having been in use for several years past at University College, London. Also plant erected in other places to the designs of the Author, in which gas or oil engines, alternators, high tension transformers, condensers, and oscillation transformers had for long been employed.

No. 749,436, dated June 17, 1903.—This specification covers a device in the form of a rheostat to be inserted in the circuit of the aerial at the receiving station for indicating the distance of the sending station. The practical value cannot be judged from the specification.

No. 758,517, applied for September 21, 1903.—This specification covers other devices intended to enable the distance of a sending wireless station to be determined by measuring the amount of damping or choking required to reduce by a regulated amount the signals being received. Seeing, however, that the intensity of electromagnetic waves arriving at a receiving station depends upon the state of the atmosphere as regards ionization due to sunlight and atmospheric electrical conditions, also on the surface over which the waves travel, it is doubtful if such devices have much practical value.

No. 750,180, applied for June 17, 1903.—The patentee here describes a method of starting into existence the oscillations in an electric wave producing radiator of the ordinary type, which consists in placing the spark balls at a distance just too great to permit the discharge of the induction coil or transformer to pass, and then starting the discharge of the condenser into operation by throwing upon the spark either ultraviolet light, or else discharging near them a small pilot spark, which serves the same purpose.

No. 778,818, applied for May 28, 1904.—This specification describes a form of

aerial consisting of a grid in connection with an electrolytic receiver. The grid is capable of being turned round a vertical axis into various positions, and the maximum indication is given by the receiving instrument when the screen or grid is broadside on to the direction of the waves. It is then stated that the grid will collect the largest amount of electromagnetic energy, and the patentee says that with the collecting screen 6 feet high and 15 feet wide he has been able to locate with certainty the position of a transmitting station 7 miles distant within 10 degrees of azimuth.

No. 771,819, applied for May 28, 1904.—In this specification the patentee describes apparatus intended to localize or determine the direction of the sending station. The receiving antenna is to be horizontal, and connected at one end through a wave-detecting device to the earth. This antenna is to be pivoted at the earthed end, so as to be capable of being swung round into various directions, and the response of the wave-detecting device will be greatest when the free end of the antenna points in the direction of travel of the waves. This receiving antenna is described as being short, compared with a quarter of the length of the received waves. A closed-loop receiving antenna is also described, formed of a long, narrow, rectangular circuit, of which the vertical sides are the shorter; and this is to be capable of being swung round a vertical axis into various azimuths.

No. 771,820, applied for June 8, 1904.—This specification describes the insertion of two choking coils in the circuit of an alternator, used in a transmitting station for preventing electrical oscillations from getting back into the alternator armature. The device was employed by the Author more than three years previously, and is an obvious application of the power of an inductance to resist the passage of a high frequency current.

No. 772,878, applied for June 20, 1903.—This specification describes a magnetic detector with divided iron core, similar to the one previously described by the Author in a paper to the Royal Society, entitled "A Note on a Form of Magnetic Detector for Hertzian Waves adapted for Quantitative Work." See *Proc. Roy. Soc. Lond.*, 1903, vol. 71, p. 398, sent in February 11, 1903.

No. 772,879, dated October 18, 1904.—This is a divided portion of the patent 749,434, applied for June 4, 1903.

No. 772,879, applied for June 4, 1903.—This is a specification for a method for simultaneous sending and receiving by means of suitably arranged and syntonized commutators which connect the antenna alternately to sender and receiver.

No. 802,850, applied for September 21, 1903.—This is for a method of starting the main condenser discharge by a small auxiliary or "trigger" spark.

Nos. 802,981 and 802,982, applied for December 10, 1902.—These are for an antenna of loop form which can be used as a loop or magnetic circuit antenna having small damping for receiving, but as an open circuit antenna with large radiative power for sending, and other details.

No. 806,966, applied for January 25, 1904.—Is for another form of antenna, which also acts as an open circuit radiator and as a closed circuit receiver.

No. 822,936, applied for February 2, 1906.—Covers an arrangement of antenna which is intended to be monoperiodic or to radiate only waves of one period.

No. 824,003, applied for February 20, 1906.—Another patent for arrangements of antenna circuits intended to be monoperiodic.

No. 824,637, applied for January 18, 1906.—A patent for a glow lamp oscillation detector identical in nature with the Author's oscillation valve previously described in U.S.A. Patent No. 803,684, applied for April 19, 1905.

No. 825,402, applied for December 9, 1905.—Describes arrangements intended to obviate the disturbing effects of atmospheric discharges. He makes use of the "oscillation valve" or glow lamp detector invented by the Author.

Nos. 836,070 and 836,071, applied for May 19, 1906.—These specifications describe a glow lamp detector, a replica of the Author's previously described instrument of the same kind. The patentee proposes to employ a telephone having a battery having a voltage from 25 to 110 volts in series with it.

No. 837,901, applied for February 14, 1906.—Covers an oscillation valve or glow lamp oscillation detector made with a mercury anode. The volatilization of the mercury under the action of the heated filament soon spoils the vacuum, and such an arrangement is therefore not serviceable. The inventor also states that the detector becomes more sensitive when it is placed in a magnetic field.

No. 841,386, applied for August 27, 1906.—In this specification the patentee describes a glow lamp oscillation detector, which he names an "audion," but which, like the previously described oscillation valve of the Author, consists of a

glow lamp which may have a filament of carbon or of tantalum, the bulb having sealed into it one or two metal plates on either side of the filament. The patentee's method of using the detector consists in connecting one terminal of the filament and the metal plates by a circuit external to the bulb, which circuit contains a telephone and a service of continuous electromotive force. The plates are also connected to a receiving antenna, and one terminal of the lamp filament is to "earth."

No. 841,387, applied for October 25, 1906.—A variation of the previous specification in which an "audion" with two separate internal metal plates is employed, one of these being connected by an external circuit containing a telephone and voltaic battery with one terminal of the lamp, and the other plate by a circuit to the other terminal of the filament, this last circuit having induced in it oscillations by those created in the receiving antenna.

No. 879,532, applied for January 29, 1907.—This covers the description of an "audion" or glow lamp detector, having one plate and a metal grid in the bulb, the connections being as described in the previous specification.

No. 913,718, applied for June 25, 1907.—This specification describes a device consisting of a rotating commutator for cutting up persistent or undamped oscillations created in an antenna into equi-spaced groups of equal duration, the object being to provide a method of syntonization in which the turning is effected for the group frequency and not the oscillation frequency.

20. Patents of John Stone Stone for Electric Wave Wireless Telegraphy.—The United States patents for electric wave telegraphy granted to J. S. Stone, together with their equivalents in other countries, form a very voluminous contribution to the patent literature of the subject. Nearly one hundred United States patents have been granted to this patentee alone. In many cases these specifications are learned contributions to the literature of the subject, filled with valuable references to other sources of information.

A complete analysis of Stone's specifications would occupy too much space. Broadly speaking, they may be divided into four classes—

(i.) Those concerned with proposed methods for the achievement of syntonic telegraphy, or the isolation of receiving stations or protection of receivers from the action of vagrant waves.

(ii.) Those describing forms of wave detector or cymoscope.

(iii.) Those covering the construction of various forms of transmitting and receiving circuit, and the production of continuous trains of waves.

(iv.) Miscellaneous specifications covering devices proposed for localizing the direction of the arriving waves and other matters.

We shall briefly refer to the contents of his chief specifications:—

No. 714,756, applied for February 8, 1900; also No. 714,831, a divided portion of the above, applied for January 23, 1901.

The patentee describes in these specifications the inductive coupling of an aerial and closed oscillation circuit by the use of an oscillation transformer, and in some cases he interposes one or more closed oscillation circuits between the aerial and the spark circuit or final receiving circuit. Stone was evidently well aware at the date of his application that in the case of inductively coupled circuits, oscillations of two periods are created in the secondary circuit, which differ in period from each other, and from the free or natural time period of the circuit taken alone.

Taking the transmitting circuit first, the patentee states that his object is to create in the aerial forced oscillations of a single frequency,

which may with advantage be the natural frequency of the aerial. This he suggests may be done by coupling the aerial inductively with another closed oscillation circuit containing an adjustable inductance, and then again coupling this last closed circuit with another in which there is a spark gap, so that oscillations are generated in the last circuit by the discharge of a condenser. There are no numerical instances in the specification, and it is not at all clear from it how the user is to proceed to adjust the inductances and capacities of the circuits so as to secure the desired result. In the same manner the receiving circuit is to consist of a number of inductively connected circuits in resonance with each other, the object of which is to facilitate the transmission to the cymoscope of oscillations having that definite period, but to prevent stray or vagrant waves of other period from affecting it.

No. 12,149 is a reissue of the above specification (No. 714,831), dated August 25, 1903. Application for reissue filed July 22, 1903.

The two above-mentioned specifications should be read in connection with the following United States patents of Stone, which are closely connected with them :—

No. 714,832, applied for January 23, 1901.
No. 12,151, a reissue of the above, dated September 8, 1903.
No. 714,833, applied for January 23, 1901.
No. 12,152, a reissue of the preceding patent, dated September 8, 1903.
No. 714,834, applied for August 8, 1902.
No. 12,141, a reissue of the preceding patent, dated August 4, 1903.
No. 767,975, applied for November 24, 1903.
No. 767,976, applied for November 24, 1903.
No. 767,984, applied for November 25, 1903.
No. 767,989, applied for December 19, 1903.
No. 767,990, applied for December 19, 1903.

The two last are a divided application of the patent No. 767,984, of November 25, 1903.

All these specifications cover in various ways the inductive coupling of an aerial with the nearly closed oscillation-producing circuit which contains a spark gap. The invention which they purport to protect is the production of oscillations in an aerial earthed at the lower end and insulated at the upper end in such fashion that "forced oscillations of a single period" are created in this aerial. Stone proposes to do this, in the first place, by inserting in the nearly closed oscillations circuit containing the spark gap a large inductance, so as to swamp the effect of the mutual inductance of the two circuits in generating oscillations of two different frequencies in the secondary circuit. We have already explained that if L and N are the two separate inductances of two circuits inductively connected together with a coefficient of mutual inductance, M, then the reaction between the circuits depends on the coefficient of coupling $\frac{M}{\sqrt{LN}}$. Hence we can make this quantity small either by decreasing M or by increasing L.

The object the patentee has in view is the radiation of waves of one single frequency of simple harmonic form, and his proposed means of achieving this consists in reducing the reaction of the open circuit on the closed energy-storing oscillation circuit by making the

inductive coupling "loose," or else by inserting inductance in the closed circuit and producing a forced oscillation in the aerial, which has a period dependent on the constant of the closed circuit, but not those of the aerial itself.

In the specification (U.S.A.) No. 767,975, of November 24, 1903, Stone explains at some length wherein he thinks his mode of inductive coupling differs from that of Marconi, as described in the latter's British patent, No. 7777, of April 26, 1900.

No. 767,979, applied for November 24, 1903.—This is for the production of "forced oscillations" in an aerial consisting of a plurality of wires.

It is difficult to understand how it is that the United States Patent Office grants patents (popularly supposed to be after careful search for anticipations) for such obvious combinations of ancient elements. At the date of this specification Marconi had employed multiple aerials of various forms for several years, and the production of forced oscillations in them is an obvious application of existing knowledge.

In the next place we come to four specifications :—

No. 767,986, applied for November 25, 1903.

No. 767,988, applied for December 8, 1903.

No. 767,998, applied for February 15, 1904.

No. 767,999, applied for February 15, 1904.

The last three being divided applications of the first named.

These specifications include numerous claims for employing large elevated horizontal plates as antennæ. Having regard to the fact that Marconi, in his first British patent specification, in 1896, had described the use of elevated plates, or cylinders, and insulated conductors, generally used as aerials or radiators in electric wave telegraphy, it is difficult to see that any novelty can be considered to attach to the claims for these arrangements in the specifications numbered above.

No. 767,983, applied for November 25, 1903.—This specification covers a method proposed for producing continuous trains of electric waves. It appears to consist in the use of a battery of high resistance, associated with a spark gap and inductively coupled to an aerial.

No. 767,993, dated August 16, 1904.—Is a divided application of the above specification.

No. 716,134, applied for January 23, 1901; No. 12,148, a reissued patent corresponding to No. 716,134, dated August 18, 1903; No. 716,135, applied for January 23, 1901.—These three specifications disclose a method for locating the direction of the sending station or source of the electric waves which consists in employing at the receiving station two aerials placed at one half of a wave length apart. These are capable of being rotated in azimuth and are connected to one receiver, so that if oscillations are created in the aerials, differing in phase by 180 degrees, the cymoscope is not affected. This device may look well on paper, but the weak point in it is that it could not be effective with solitary or aperiodic waves nor with short highly damped trains of waves.

It is based on the assumption that equal and opposite oscillations can be generated at the same time in the two aerials, and also upon the use of a relatively short wave. It could hardly be employed with waves having a length of 1000 feet or more. It presupposes the use of very long slightly damped trains of electric waves of wave lengths not exceeding 200 or 300 feet.

Nos. 717,511, 717,512, application of January 23, 1901.—These two specifications cover the description of a proposed method for increasing the time period of oscillation of an aerial by clothing it with a dielectric sheath which may have embedded in it ferromagnetic material in a state of powder. Unless the dielectric sheath was enormously thick it would not have much effect, and the magnetic hysteresis of the ferromagnetic powder would probably assist in greatly damping the oscillations. Very much the same idea was subsequently placed in other patent specifications by R. A. Fessenden.

No. 768,000, applied for February 23, 1904.—This covers a form of multiple spark ball discharger placed in a box in which air or other gases may be compressed.

No. 768,004, applied for April 11, 1904.—This specification describes numerous

forms of aerial in which the spark gap is short-circuited either by a condenser or by a condenser in series with inductance. The patentee gives a useful and extensive series of references to the literature of the subject, and states that the first use of a condenser shunting a spark gap was due to Blondlot.

We then reach a group of specifications by Stone which are chiefly concerned with thermal and electrolytic receivers, the thermal receivers being in some cases bolometer detectors; that is, dependent on the heating effect of an electric oscillation on a very fine wire, and in other cases on the use of thermoelectric couples.

These specifications of Stone are full of useful references to original papers on the bolometer and kindred subjects, and are, in fact, a learned exposition of the whole subject.

The principal specifications are as follows:—

No. 767,971, applied for August 11, 1902.—This deals with the construction of a bolometer detector made with fine wire. The patentee describes the advantages of bismuth wire in place of iron or platinum. He gives copious references to the literature of the bolometer and to the form of oscillation bolometer used by Rubens and Ritter (which he adopts) and others. The arrangements are, in fact, the combination of a Rubens and Ritter bolometer with an aerial receiver and earth connection.

No. 767,972, applied for September 10, 1902.—This is a divided application of the patent No. 767,971.

No. 767,980, applied for November 5, 1903.—This specification also contains very useful notes on the bolometer, but is principally concerned with the application of a bolometer detector to a duplex receiving aerial, so arranged that by rotation in different azimuths the direction of the arriving waves may be determined, these aerials being separated by a distance equal to half a wave length (see also Stone's U.S.A. specification, No. 716,134).

No. 767,981, applied for November 25, 1903.—Deals with a special form of bolometer cymoscope consisting of a very thin strip of gold leaf, which is cast into paraffin and cut to the required small size by a microtome. The rise in temperature produced when electric oscillations pass through it is to be detected by its change in resistance. In this specification very useful references are given to Wollaston's original paper containing the account of his method of making ultra-fine platinum wire, and to other books where the process is described.

No. 767,992, applied for January 15, 1904.—This is a divided application of the above patent, No. 767,981.

No. 767,985, applied for November 25, 1903.—This contains a description of a mode of manufacturing a thermoelectric pile of platinum and gold for use as an oscillation detector.

No. 767,987, applied for December 8, 1903.—This is a divided application of the foregoing patent, No. 767,985, for a thermoelectric receiver.

Nos. 767,996 and 767,997, applied for February 15, 1904.—These two specifications cover a form of thermal receiver. It consists of a fine Wollaston platinum silver wire with platinum core and silver exterior, which just dips into mercury. The mercury dissolves away the silver and leaves a short length of platinum exposed, and since mercury does not wet platinum, the patentee says that a short length of the platinum would be exposed above the mercury, on account of the capillary depression of the mercury. Its action would, however, depend entirely upon the platinum wire not being amalgamated, and it may be doubted whether the removal of the silver by the mercury could be effected completely without amalgamating the platinum wire as a result.

No. 768,003, applied for April 11, 1904.—In this specification Stone redescribes the electrolytic detector consisting of a fine Wollaston platinum wire just dipping

into nitric acid. He states that the cell is inoperative unless the fine platinum wire is made the anode. This, however, was well known prior to the date of this specification. Stone appears to agree with the opinion of Fessenden that the action of the cell is in part at least thermal, the change in resistance being due to the heating of the electrolyte under the action of the oscillations.

We then come to a group of Stone's specifications which have reference to securing the privacy of communication by electromagnetic waves. The object of these arrangements is to render a particular station receptive for waves only of one frequency, but not receptive for waves of other frequency, or of aperiodic or isolation waves.

It is impossible to say by simply reading the above specifications whether they describe real inventions which have been practically tried and found to be successful, or whether they represent simply anticipatory opinions. In the absence of definite information on this point, it is not necessary to analyze these specifications very closely.

Four specifications of considerable interest—viz. No. 716,135, applied for January 23, 1901; No. 767,970, applied for January 23, 1901; and No. 768,002, a divided application referring to an original applied for on November 25, 1902, and No. 899,272, applied for August 17, 1906—refer to a method for localizing the direction of a sending station, or rendering a receiving station receptive only to waves coming from a certain direction. They are based on the fact that if two aerials are set up at a distance equal to half a wave length they will be affected in a similar manner by a train of waves meeting them broadside on, but will have produced in them oscillations in opposite phase if subjected to the action of a wave train travelling in the direction in the plane of the aerials.

These antennæ are connected to a receiving circuit in such manner that equal oscillations in the two antennæ neutralize each other's effect, but if the oscillations are not of equal amplitude or are opposed in phase they do actuate the receiving mechanism. The chief objection which can be urged against this plan is the great length of wave now used in radiotelegraphy, which necessitates a considerable interval between the antennæ.

Three specifications—No. 725,634, applied for January 3, 1903; No. 725,635, applied for March 12, 1903; and No. 725,636, applied for March 12, 1903—also refer to complicated arrangements intended to isolate wireless telegraph stations. The signals are for the most part transmitted by means of punched paper tape, but for the elaborate arrangements suggested the reader must be referred to the original specifications.

Five other specifications—No. 767,978, applied for November 24, 1903; No. 767,991, applied for December 23, 1903 (a divided application of the previous one); No. 767,932, applied for November 25, 1903; No. 767,994, applied for February 13, 1904; No. 767,995, applied for February 13, 1903—all describe elaborate arrangements, having as their object the isolation of wireless telegraph stations, and the remarks made with reference to the previous group of specifications apply to these also.

No. 768,001, applied for February 23, 1904.—This specification describes a system for selectively receiving signals transmitted by waves of predetermined electrical frequency and predetermined group or wave-train frequency.

Several specifications have been filed by Stone, the objects of which are to describe arrangements intended to permit transmission and reception to be effected simultaneously at one station; that is to say, to provide a means by which the waves sent off from one aerial shall not affect or prevent the reception

of other messages from a distant station at closely adjacent aerials. Two such specifications are—

Nos. 716,136 and 716,177, applied for January 23, 1901.—The arrangement proposed is a single receiving aerial set between two transmitting aerials so arranged that these two transmitting aerials are traversed by electric oscillations in opposite directions, and therefore nullify each other's effect upon the adjacent receiving aerial. If, however, these transmitting aerials are placed at a distance equal to one wave length apart, each being half a wave length distant from the single receiving aerial midway between them, their effects will be combined together at any distant point lying in the plane of the two transmitting aerials. The patentee, however, treats the subject as if wave trains were continuous and suffered no decrement.

Other kindred specifications are—

Nos. 717,509, 717,513, 717,514, 717,516, applied for January 23, 1901.—All describe arrangements by which it is proposed to relay wireless telegraph messages, so that signals received on an aerial may set in operation apparatus which retransmits the messages from another adjacent transmitting aerial.

The practical problem here involved is one which has been attacked by numerous inventors, particularly E. Guarini, and some have claimed that they have given a solution of it, but the author is not aware that any of the proposed solutions suggested have reached the stage of practical verification.

No. 767,973, applied for October 30, 1903.—This specification is an interesting treatise on the subject of the propagation of electric waves from an earthed aerial. The advantages of a good earth are pointed out, and a number of interesting diagrams are given in the specification. The particular purpose of the specification appears to be an insistence on the advantages of a good earth connection, already at the date of the specification a well-known fact and the reasons for it understood.

No. 767,977, applied for November 24, 1903.—Deals with the advantages of quartz glass as a dielectric for high-tension condensers, and with the advantages of a core composed of a paramagnetic substance for oscillation transformers.

No. 768,005 describes a tower or mast for supporting an aerial wire, the said tower being cut up into insulated sections, and the mast supported by stays in the same way, divided into sections by insulators. This last method of supporting a mast, as used for a wireless telegraph aerial, had been in public use by Marconi for some years before the date of this specification of Stone.

For information on other and later radiotelegraphic patents of Stone, lists of United States Patents must be consulted.

21. The Work of other United States Patentees and Inventors in Radiotelegraphy.—Another extremely industrious patentee in the United States is H. Shoemaker, who is accountable for more than forty patents on the subject between 1901 and 1905. His specifications comprise mechanical devices for conducting multiplex radiotelegraphy, improvements in coherers, various wave detectors, and sundry devices for improving the transmitter. None of them are, however, of sufficient importance to make it worth while to abstract them seriatim. The most useful contributions which have been made to the subject by United States inventors have been in the direction of improved forms of detectors. General Dunwoody of the United States Army discovered in 1906, that a crystal of carborundum (carbide of silicon) possessed a unilateral conductivity for electric oscillations, and could therefore rectify them and serve as a detector of electric wave trains when associated with a telephone as explained in Chap. VI. (see United States specification of H. H. C. Dunwoody, No. 837,616, applied for March 23, 1906). This was followed by the discovery by Professor G. W. Pierce of similar properties in several other crystals, and of a peculiar property

of rectifying oscillations possessed by the contact between certain substances such as molybdenite and a copper point pressed against it. Pierce discovered the rectifying power of hessite (a native telluride of silver), octahedute and brookite, and anatase (a native oxide of titanium), and also of hematite and coovellite. It had long previously been known that psylomelan possessed a marked asymmetric conductivity (see U.S.A. patents of G. W. Pierce (No. 879,061, 879,062, 879,117 and 923,700). Also several such asymmetric conductors composed of two substances, such as a brass point and a solid oxide of zinc surface, were discovered by G. W. Pickard (see U.S.A. patent No. 924,827). The details of some of these detectors have been discussed in Chap. VI. in giving descriptions of various wave detectors. These rectifying detectors used in conjunction with a telephone are simple, inexpensive and easily adjusted, and hence have found extensive use.

22. Radiotelegraphic Inventions in France, Italy, and other Countries.—In addition to the pioneer work of M. E. Branly, the inventor of the metallic filings cymoscope, valuable scientific work has been done in France by MM. A. Blondel, C. Tissot, P. Janet, H. Poincaré, J. Ferrie, and A. Turpain. M. Tissot's work has been chiefly in connection with quantitative measurements, and a valuable *résumé* of these is found in his book, "Sur le Résonance des Systèmes d'Antennes," published in 1905. He employed the bolometer bridge as his instrument of research, and contributed much to the quantitative study of radiotelegraphy. The scientific writings of Professor A. Blondel and of Professor H. Poincaré have been most valuable in elucidating the subject.

In Italy MM. Bellini and Tosi have contributed work of much utility in connection with directive radiotelegraphy, which is considered in detail in Chap. VIII.

Apart from the problem of generating and radiating prolonged trains of waves and controlling them for signalling purposes, and detecting them by the simplest means, the attention of inventors has been largely directed to the problem of increasing the privacy of communication.

We have already indicated the method based on syntony between the oscillation periods of the sending and receiving apparatus, but many other methods have been tried.

Inventors have endeavoured to solve this problem by devising methods in which the syntonism between the stations is not that of the frequencies of the waves, but the much lower frequency of the wave trains. Thus a series of groups of waves may be sent out from a transmitting station, each wave train consisting, say, of 200 waves, having a frequency of 1,000,000. Then the whole wave train would occupy only one five-thousandth of a second. The wave trains might follow each other with a frequency of 100. Then 100 trains of waves would pass any point per second, and the so-called group frequency would be only one-fiftieth part of the wave frequency. It is then possible to construct receiving apparatus which shall be sensitive only to the group frequency.

The original suggestion for this method of working came from M. A. Blondel, who, on August 6, 1898, deposited with the Academy

of Sciences in Paris a sealed envelope containing a description of his improvements in syntonic wireless telegraphy which was opened on May 19, 1900.[48]

From the transmitter trains of electric waves are sent out at definite intervals controlled by a regular interrupter. At the receiving end a single voltaic cell keeps a condenser charged until a cymoscope of the metallic filings type is rendered conductive by the oscillations created in the receiving aerial by the waves falling on it. Under these circumstances the condenser discharges through a telephone. The telephone used, however, is one of the Mercadier monotone telephones, or some equivalent form which does not respond to a single current or discharge through it, but only to a regulated series of currents at certain intervals, say 100 per second. Hence, if the wave trains continue to arrive at these intervals they will create a sound in the telephone, and this may be shorter or longer to correspond with a Morse dot or dash, according as the key at the transmitting end is manipulated. The receiver will, therefore, be insensitive to irregular or aperiodic impulses, but sensitive to wave trains, or even solitary waves, arriving at the determined rate fixed by the timing of the monotone telephone.

That this may be achieved the sparks or trains of oscillations in the transmitter must be separated by exactly equal intervals of time, and when induction coils or even transformers are used this is very far from being the case.

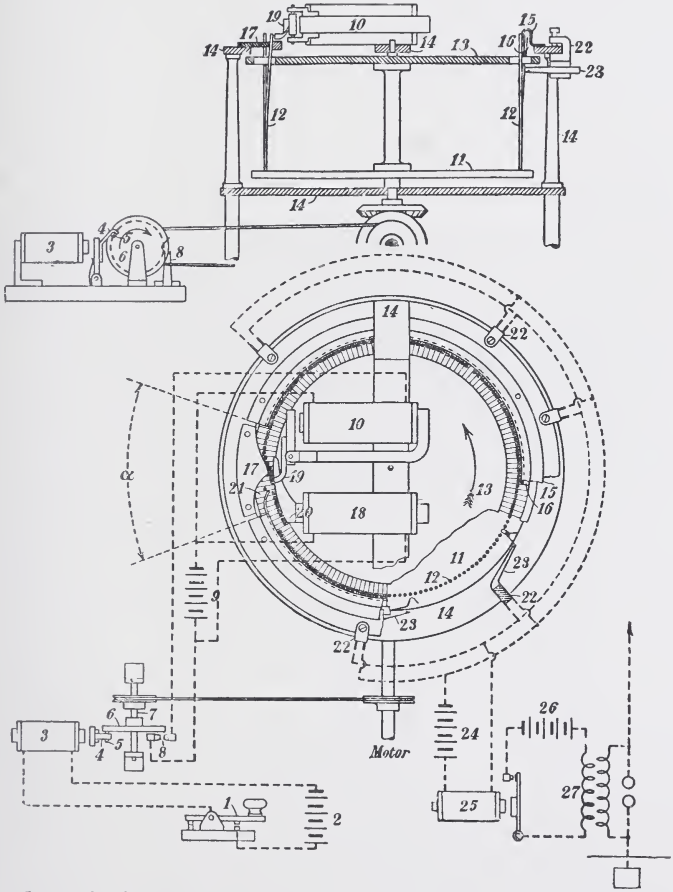
Hence these methods, though they look well on paper, have never been reduced to successful practice.

We may then pass on to notice briefly the attempts that have been made to secure isolation by a plan which is not dependent on electrical syntony. One of these is that due to Anders Bull.[49] In the first arrangements proposed by this inventor, a receiver is constructed which is not capable of being acted upon merely by a single wave or train of waves, or even a regularly spaced train of electric waves, but only by a group of wave trains which are separated from one another by certain unequal predetermined intervals of time. Thus, for instance, to take a simple instance, the transmitting arrangements are so devised as to send out groups of electric waves, these wave trains following one another at time intervals which may be represented by the numbers 1, 3, and 5; that is to say, the interval which elapses between the second and third is three times that between the first and second, and the interval between the third and fourth is five times that between the first and second. That is achieved by making four electric oscillatory sparks with a transmitter of the ordinary kind, the intervals between which are settled by the intervals between holes punched upon strips of paper, like that used in a Wheatstone automatic telegraphic instrument. It will easily be understood that by a device of this kind groups of sparks can be made, say four sparks rapidly succeeding each other, but not at equal intervals of time. One such group constitutes the Morse dot, and two or three such

[48] See *Comptes Rendus*, May 21, 1900, vol. 130, p. 1383, "Sur la Syntonie dans la Télegraphie sans fil;" or, "Rapports du Congrés International d'Electricité," p. 341. Paris, 1900.

[49] See *The Electrician*, February 8, 1901, vol. 46, p. 573.

groups succeeding one another very quickly constitute the Morse dash. These waves, on arriving at the receiving station, are caused to actuate a punching arrangement by the intermediation of a coherer or other cymoscope, and to punch upon a uniformly moving strip of paper holes which are at intervals of time corresponding to the intervals between the sparks at the transmitting stations. This strip



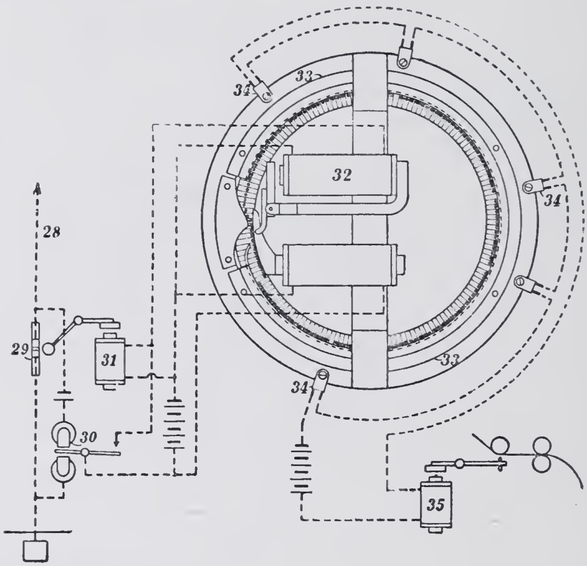
From "The Electrician."

FIG. 72.—Diagram of Connections in the Anders Bull Transmitter for Electric Wave Telegraphy.

of paper then passes through another telegraphic instrument, which is so constructed that it prints upon another strip a dot or a dash, according to the disposition of the holes on the first strip. Accordingly, taken as a whole, the receiving arrangement is not capable of being influenced so as to print a telegraphic sign, except by the operation of a series of wave trains succeeding one another at certain assigned unequal intervals of time.

To carry out these principles in practice, two instruments have to be employed. At the transmitting end one to effect the conversion of Morse signals, made with an ordinary key with the properly spaced series of wave trains radiated from the aerial. This is called the disperser. At the receiving station another instrument called the collector is employed to effect the reconversion of the wave groups into the Morse signal printed on a Morse inker. The arrangements are shown in the diagrams in Figs. 72, 73, 74, and 75, taken, by permission, from an article by M. Anders Bull in *The Electrician*.[50]

If a dot in the Morse code is to be transferred from a station, A, to another station, B, a series of, say, five wave impulses at intervals a', b', c', and d' is despatched. The receiver at B, tuned for these



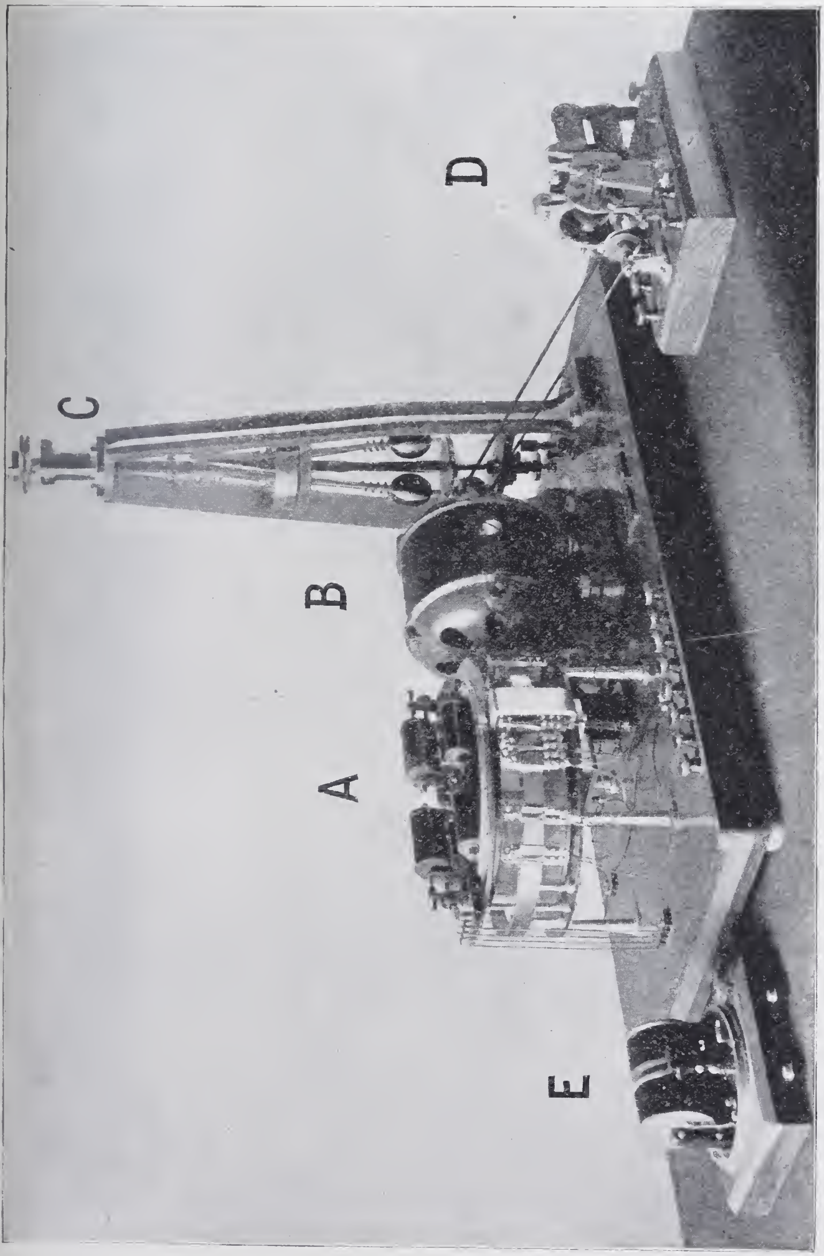
From "The Electrician."

FIG. 73.—Diagram of Connections in the Anders Bull Receiver for Electric Wave Telegraphy.

intervals, collects the five impulses and registers them as a dot on the tape of a Morse apparatus; in transmitting a dash, a sequence of such series is despatched from A, and the receiver at B will register a row of closely placed dots (a dash) on the tape. If A wants to communicate with another station, C, a second series is used, the intervals being a'', b'', c'', and d''. These series will not be recognized by the receiver at B, as the intervals do not correspond with the adjustment of the latter. The receiver at C will, however, receive and record the signal. In this way, by using series of different forms, one can telegraph selectively from a transmitting station to any number of receivers.

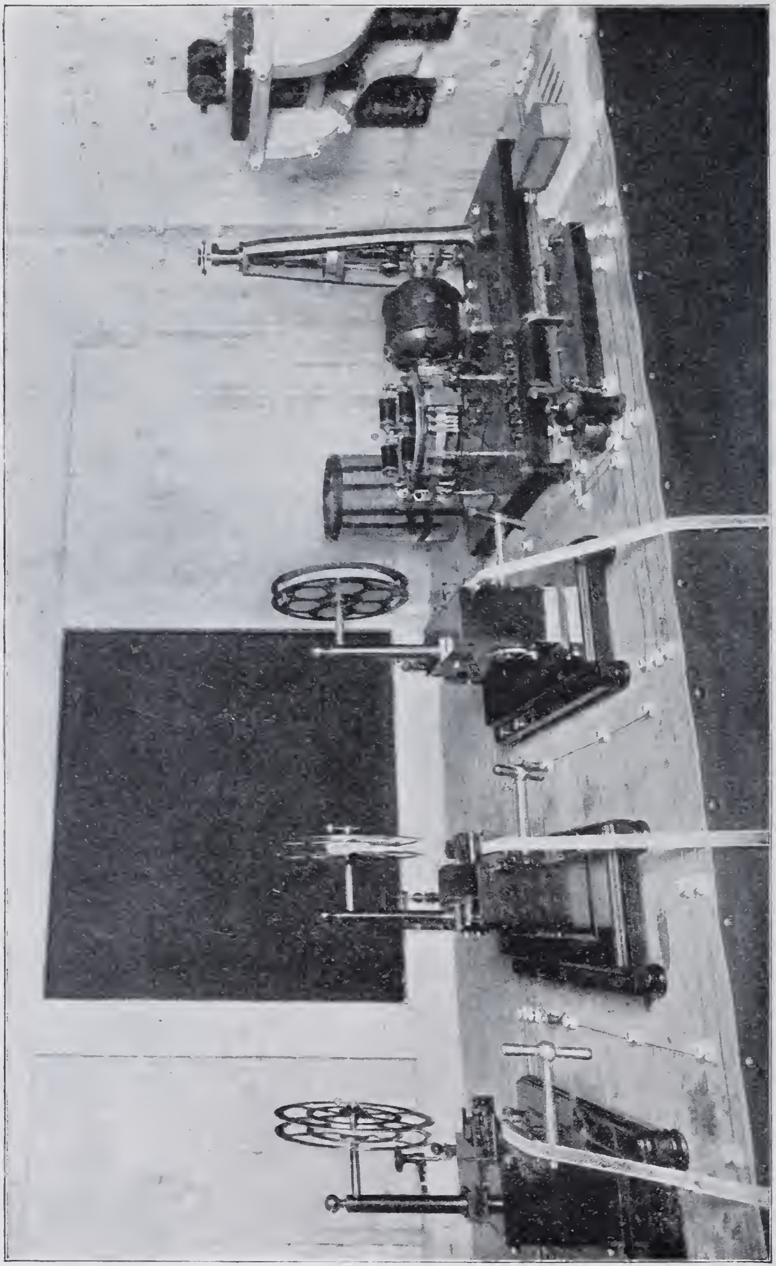
The conversion of the Morse signs into series at the transmitting

[50] See *The Electrician*, January 2, 1903, vol. 50, p. 418.



From "The Electrician."

FIG. 74.—View of Transmitting Apparatus used in Anders Bull System of Selective Wireless Telegraphy.



From "The Electrician."

FIG. 75.—View of Receiving Station, showing Three Independent Receivers in Anders Bull System of Selective Wireless Telegraphy.

station, as well as the reconversion of the series into dots at the receiving station, is accomplished automatically by two instruments, the disperser and the collector, respectively. Sending is carried out in the usual way by pressing down a Morse key for short or long periods.

Fig. 72 shows diagrammatically the connections at the transmitting station. By pressing the key 1, a current will flow from the battery 2 through the windings of the electromagnet 3, the armature of which is fitted with a hook, 4, to grasp the stop 5 on the disc 6. The latter is loose on the pivot 7, which rotates with a velocity of about five revolutions per second, the friction being sufficient, however, to confer on the disc a tendency to rotate with the pivot. When, therefore, the armature is attracted, the disc 6 is released and starts rotating; the stop 5, in passing the contact springs 8, will close a circuit, including the battery 9, and the electromagnet 10, mounted on the frame of the disperser. If the key is pressed only for a short time (in order to send a dot), the hook, having released the disc, resumes its normal position, and the disc is stopped after one revolution. Only one impulse is then sent through the windings of the magnet 10. If, however, the key is pressed long enough to allow the disc to make several revolutions, a number of impulses at regular intervals of one-fifth of a second are sent round the magnet.

The disperser consists of a disc, 11, to which is fixed a large number of concentrically arranged vertical steel springs, 12. The upper ends of the springs are free, and are passed through radial slots in a second disc, 13; their ends are thus allowed freedom in a radial direction only. The two discs are mounted on the same spindle, and revolve within the frame 14, to which is fixed a ring, 15, serving as a guide for the points, so that during a revolution they are caused to glide either within the ring or in the $\cap$-shaped groove, 16, formed by the latter. A piece of the ring corresponding to the angle a (Fig. 72) is cut off, and in its place is fitted a piece of bronze, 17, which bends the ends of the springs towards the pole of the magnet 18. This magnet is constantly excited by current from the battery 9, and the steel springs are attracted by it. Their elasticity being overcome by the strength of the magnet, and the bronze finger 19 being in its normal position, the springs will slide along the pole of the magnet 18, and will not be released until they have reached the edge 20. On further revolving, they will glide within the ring 15. If, on the contrary, the magnet 10 is excited, the finger 19, fixed to the armature, will be pushed over the pole of the magnet 18, and protrude slightly in front of it. Then when the springs pass by this finger, they will be forced from the pole of the magnet 18, and on account of their elasticity will resume their vertical position. They will, therefore, enter the $\cap$-shaped groove at 21, and remain in the latter for one complete revolution.

Around the circumference of the disperser a number of contact devices, 22, are fitted, consisting of two contact springs, 23, insulated from each other; by the aid of screws these devices may be fastened around the frame at any desired angular intervals. The contact springs are arranged in such a way as to allow the steel springs moving within the ring 15 to just clear them, while the steel springs

in the groove 16 protrude, and therefore in passing, will establish contact. When the disperser is working, provided the magnet 10 has not been excited, all the steel springs will glide within the ring 15, and consequently all the contact devices 22 will be open. If, however, a short current impulse is sent through the windings of the magnet 10, a steel spring is brought into the groove 16, and establishes contact successively at every one of the contact devices. The contact springs are electrically connected, as shown in Fig. 72, and, accordingly, each time a contact is made, current from the battery 24 will excite the interrupter magnet 25, the armature of which will be attracted, causing a current from the battery 26 to flow through the induction coil 27. On the subsequent opening of the circuit, a spark discharge takes place between the secondary terminals of the coil, and a wave impulse emanates from the transmitting station. Consequently, for each current impulse that is sent through the windings of the disperser's magnet 10, a number of wave impulses corresponding to the number of the contact devices 22 are despatched. The discs revolving at approximately constant speed, the time intervals between the impulses of such a series will be proportional to the angular distances between the contact devices, and by putting these in different positions around the frame of the disperser, one can vary the form of the despatched series at will.

At the receiving station the wave impulses strike the mast wire 28 (Fig. 73), lowering the resistance of the coherer 29, and causing the relay 30 to become excited. The latter closes the circuit for the tapper 31, by which the initial resistance of the coherer is restored, and at the same time a current impulse is sent through the windings of the collector magnet 32, which is shunted with the tapper. As the collector is constructed in the same way as the disperser, a steel spring for each arriving wave impulse is brought into the groove of the ring 33. The disc to which the steel springs are fastened, like that of the disperser, revolves at approximately isochronous speed, and consequently the angular distances between the springs brought into the groove will be proportional to the intervals of time between the impulses that have impinged upon the mast wire 28. A series of, say, five impulses will, therefore, cause five springs to be brought into the groove at angular intervals corresponding to the intervals of time between the impulses. Around the frame of the collector are fitted the same number of contact devices, 34, as are on the disperser, and, similarly, only the springs moving in the groove will be able to establish contact. The contact devices of the collector are, however, connected in series (Fig. 73), so that a current cannot flow through the Morse apparatus 35 until contact is established simultaneously at all the points. If now these points are adjusted to the same mutual angular distances as the steel springs, which, on the arrival of a certain series of impulses, are brought into the groove, then such a group of steel springs will, during the revolution of the disc, cause a momentary simultaneous contact at all the points; a current impulse then flows through the Morse apparatus, and is registered as a dot on the tape. Consequently, a continuous succession of series, despatched by the transmitter when a dash is to be transferred, is registered as a continuous row of dots. Series of any other form

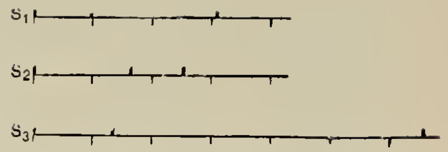


FIG. 76.—Signal Forms used in Anders Bull System of Selective and Independent Wireless Telegraphy.

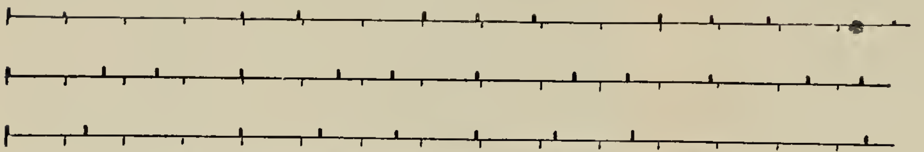


FIG. 77.—Signal Codes in Anders Bull System of Selective Wireless Telegraphy.

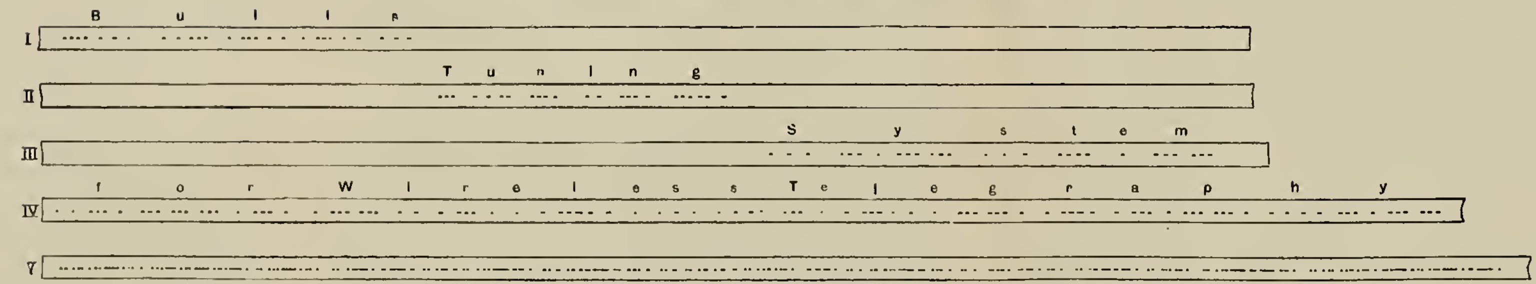


FIG. 78.—Reproduction of Morse Tapes, showing Independent Messages received simultaneously by the Anders Bull Apparatus for Selective Wireless Telegraphy.

[*To face p.* 627.

than the one to which the collector is adjusted cannot cause a simultaneous contact of the devices 34, and therefore they will not be registered by the Morse apparatus.

Fig. 74 shows the instruments used in the experiments. The disperser and collector are here combined in one apparatus, A, one half serving for despatching and the other for receiving messages. The apparatus is geared to a small motor, B, the speed of which is regulated by a brake regulator of the Siemens and Halske type, C. The disc carrying the steel springs is rotated at a speed of about one revolution per second, and the number of the springs is 400. D is the automatic device above indicated by 3–8 in Fig. 72, and is worked from the shaft of the motor. E is a relay, designed for rapid acting, the armature being very slight and the iron core laminated. It works well with 0·1 of a milliampere.

At the time of writing the above description, the inventor had only been able to mount one transmitting and one receiving station, but he had provided the disperser with three sets of contact devices 34, any one of which could be put in connection with the interrupter of the induction coil by means of a switch. The same key could be used to despatch series of three different forms, and at the receiving station the collector was provided with three sets of contact devices, each of which was connected to a Morse apparatus; these being adjusted in such a way as to correspond with the three forms of series to be despatched from the transmitting station. Fig. 75 shows the complete receiving station, with three independent Morse printers.

The number of impulses in each series is only three, and S_1, S_2, and S_3 in Fig. 76, show diagrammatically the three forms used. Time is represented by the length of the horizontal line, and the impulses by heavy cross strokes. The distance between two of the fine cross strokes represents 0·05 of a second. In Fig. 77 is shown how the series succeed each other when the key is pressed for a long time. By aid of these three series it was possible to telegraph selectively to any of the three Morse machines at the receiving station. The messages arrived very distinct and precise, and appeared exclusively on the tape of the machine for which they were intended. I. to III. in Fig. 78 shows three pieces of tape simultaneously unwound from the three Morse machines, when words were sent by the transmitter, in each of the three series S_1, S_2, and S_3 successively. The tapes show that when one machine was working no signal was registered by either of the other two.

As far as the author knows, this is the greatest number of receivers that, up to the present, have been worked selectively by wireless telegraphy; but it is evident, however, that they may be increased by varying the forms of the series. The different transmitters and receivers will work equally well if mounted at different stations, and it is quite immaterial whether the distance to be covered is great or short; in these respects the present system possesses an advantage over those based on electric syntony. The working distance over which these experiments were carried out was only about 100 yards, the energy of the transmitter being small in proportion. Several despatches can be simultaneously transmitted by this system

without interference; but, unfortunately, the inventor was unable to experiment in this direction owing to the lack of apparatus at his disposal.

It might be thought that the speed of working must be very limited, a dot requiring a series of at least three impulses; but this objection is justified only to a certain extent, as the dashes hardly require more impulses than by other systems. The dashes may, without fear of confusion, consist of only two dots, and two series are therefore sufficient, making six impulses a minimum for the transference of a dash. Although no arrangements for great speed were made in these experiments, fifty letters a minute were easily transmitted, and this speed could be considerably increased. The system may also be, with little difficulty, adapted to the Hughes type-printing apparatus. The greatest advantage, however, lies in the fact that it is impossible for an outsider to "overhear" or "tap" a message. The lack of secrecy has always been one of the disadvantages urged against wireless telegraphy as an argument against its commercial utility, but it is possible that this system, or some modification of it, may present advantages in certain cases.

Anders Bull has also suggested methods for rendering messages unintelligible to those unconcerned; one is to make the intervals of time between the impulses in the series so long that the latter become somewhat longer than the intervals between each of the series, which are despatched in continuous succession when the key is pressed for a dash. This is the case with the series S_3 in Fig. 76. When telegraphing, the series will then overlap each other in a way which makes the message unintelligible if recorded in the usual manner. This is plain from tapes IV. and V. (Fig. 78), which were simultaneously unwound from two Morse machines, one being tuned and the other connected to the coherer in the ordinary way. The latter machine, of course, registers each impulse in the order of arrival, and the message appears as on tape V. Tape IV. is the identical message recorded by the tuned receiver, and it should be observed that the series in this case only consisted of three impulses. When a greater number is chosen the messages recorded by an ordinary receiver will be still more confused. The other way of keeping the messages secret is to use short series, as S_1 and S_2 in Fig. 76, and to send out in the spaces between the individual dots and dashes of the message a series of a form not affecting the receiver telegraphed to, but nevertheless resembling the series to which the receiver is tuned; this can be done by a very simple automatic device. In such a case an ordinary wireless telegraph receiver would give an unbroken row of dots, quite impossible to decipher, as the two forms of series could not be separated.

The following is an account of some tests carried out before the United States Navy with the Anders Bull system of selective wireless telegraphy, described in *The Electrician*, vol. xlvi. p. 573; vol. l. p. 418; and vol. li. p. 963. The tests were undertaken between the Government stations at Highlands of Navesink, N.J., and Brooklyn Navy Yard, the distance being about thirty-five kilometres. The field is considered a rather difficult one for experimental work, as the waves have to pass the greater part of Brooklyn; moreover, the

stations are very much troubled by interference from several other wireless installations in the neighbourhood, the interference lasting sometimes without interruption for hours.

The regular service between the said two stations is performed by means of the Slaby-Arco system, which has been provisionally adopted by the United States Navy. It was decided to try the Anders Bull selective instruments in connection with the existing installation. The instruments were employed as already described. The voltage used at Navesink and Brooklyn is 80 and 110 volts respectively; as, however, the transmitter was only constructed for low voltage and small power, it was only possible to use a fraction of the energy generally employed for signalling between the stations. Thus, while the spark is usually about $\frac{3}{4}$ inch long, the tests had to be made with $\frac{5}{32}$ inch spark. In order to get good communication, it was necessary to make the receiving arrangement very sensitive. This, however, made the conditions for the tests rather unfavourable, as sensitive instruments are much more exposed to disturbances of all kinds, and do not work with the same exactness and rapidity as less sensitive ones. Of course, difficulties of this nature can be easily overcome, as the transmitter can be constructed for any energy required; but for the tests in question no other apparatus was at hand.

The transmitter was installed at Navesink, the receiver at Brooklyn Navy Yard. Lack of apparatus prevented them from signalling selectively in both directions. At both places switches were provided, so that either the Slaby instruments or the Anders Bull apparatus could be connected up to the oscillation circuits and aerials.

The experiments were conducted chiefly with a view to demonstrating the *secrecy* of the correspondence. Arrangements were, therefore, made at the receiving station so that the messages could be simultaneously registered by the selective inker M, and another one, M′, which was connected up to a relay in the ordinary way, thus enabling a comparison to be made between the two records. Secrecy was obtained by using a series of three impulses at intervals of 0·063 and 0·295 second, the interval between successive series being 0·2 second.

The official demonstration was conducted before the Wireless Telegraph Board. The sending was carried out by the chief electrician at the Navesink station. During the tests there were slight atmospheric disturbances, which seemed strongly to affect the communication with the Slaby-Arco instruments, while they had only very little effect on the selective signalling. A message which could not be read, in spite of its being repeated some four or five times with the Slaby instruments, was easily deciphered when sent once by the Anders Bull. In order to put the selective inker in action, at least three wave impulses correctly timed are necessary. As long as, therefore, the interference is only moderate it does not affect the selective receiver, although it may be strong enough to make correspondence with ordinary wireless instruments an impossibility. To prevent misunderstanding, it should be observed that the Slaby instruments were using the full energy the whole time. Very long

despatches were after this satisfactorily transmitted with the Anders Bull instruments, the operator at times working the key without interruption for fifteen minutes. Some tests were also performed for the purpose of ascertaining the influence of a difference in the speeds of the transmitting and receiving instruments respectively. The speed of the disperser was kept constant at 57 revolutions per minute, while the collector was made to run with speeds varying between 53·5 and 61 revolutions per minute. During the whole time the V's sent by the Navesink station came out very clearly on the tape of the selective inker. Thus, even deviations from the normal speed as great as 8 per cent. could be allowed. It is advisable, however, in order to get a distinct tuning, that the variations should be the smallest possible.

Comparisons between the tapes unrolled by the selective inker M, and the ordinary one, M′, proved the complete impossibility of outsiders tapping the messages. Any wireless signalling is apt to be interfered with, especially when carried out over long distances. Some dots may fail, new ones may appear (for instance, by atmospheric disturbances), or a dash may be split up into dots; in this way letters may easily be mistaken. As long as ordinary language is used scattered faults of this kind are not of much importance, as they are generally easily detected by the context of the message. When code is used the case is different. The mistake of a few letters may here make the whole message illegible. Besides, the use of code requires skill, and is very time-wasting work, even if the messages come in perfectly clear, and there may be occasions where the minutes are valuable; for instance, during war.

Another system for which an advantage is claimed in connection with syntonic telegraphy is that of Alessandro Artom, who has proposed to employ a circularly or elliptically polarized beam of electric radiation.

This inventor has described in two British patent specifications his appliances, as follows.[51] He erects two aerial wires at right angles both at 45° to the vertical. In these aerials he states that he can generate by the usual method of condenser discharge oscillations which differ in phase by 90°. It is not very clear from the specifications that the methods he proposes would be effective, because the patentee appears to neglect the fact that the radiation sent out from a linear aerial is very highly damped. To procure approximately circular polarization, it is necessary that the original beam of radiation shall have been polarized in one plane and then split into two beams polarized in planes at right angles, and one of these beams he retarded by 90° or a quarter of a period. Optically this is affected by a device called a Fresnel's rhomb. In the electrical case it is necessary to secure that the oscillations in the two aerials at right angles are not only in the right relative phase at the commencement of the oscillations, but remain different in phase by 90° throughout the train of waves, and also that both trains have the same logarithmic decrement. It is also not very clear what advantage is secured by the use of a beam of circularly or elliptically polarized radiation in regard to the

[51] See British Patent Specifications of Alessandro Artom, No. 26,395, of November 29, 1902, and No. 9408, of April 25, 1903.

privacy of communication. The method appears, however, to have been tested in Italy by the officers of the Italian Navy, with the following results, as stated in a letter addressed to the chairman of the Royal Academy of Lincei by the inventor.

It has been said that experiments were conducted in the Gulf of Spezia in February, 1903, to test the feasibility of signalling from the wireless telegraph station of St. Vito to that of St. Bartolomeo (a distance of 4 kilometres), without its being possible for the lateral stations of Varignano and Palmaria, situated a few kilometres outside the junction of the transmitting station of St. Vito with the receiving one of St. Bartolomeo, to receive any signal.

Further experiments were conducted between the radiotelegraphic station of Monte Mario (Rome) and Anzio (a distance of 60 kilometres) in the months of August, October, and November, 1903, with the same object.

The patentee asserts that when the radiator was turned towards Anzio the signals were received perfectly, whilst they ceased when, the energy employed being the same, the radiator was turned towards Sardinia.

Experiments were also tried in the months of March and April, 1904, between the wireless telegraph station of Monte Mario (Rome) and that of Ponza (a distance of 120 kilometres). It is said to have been ascertained that it was possible to send very clear signals to the receiving station of Ponza, and that one could also treble the energy wherewith such electromagnetic signals were produced, without its being possible for the receiving station located in the island of Maddalena, and situated laterally outside the junction of Monte Mario with the island of Ponza, to perceive any signal.

Experiments executed in the months of August, October, November, and December, 1904, between the wireless telegraph station of Monte Mario (Rome) and that of the island of Maddalena (a distance of 260 kilometres). These experiments are asserted to have confirmed the preceding ones.

It will be interesting to know if further researches confirm the advantage said to be obtained by the employment of such circularly polarized electromagnetic radiation.

On the whole, however, it cannot be said that any of the proposed substitutes for true electric resonance, as a means of securing the privacy of wireless telegraphic communication, have been very successful. Either they involve apparatus of considerable complexity, or else they fail to fulfil in practice the hopes of their inventors, by reason of the fact that the said inventors lose sight of the fact that much which is possible with continuous radiation ceases to be possible when we are dealing with intermittent trains of damped waves.

The systems which give greatest promise of privacy for naval use are those which, like that of Anders Bull, depend upon the emission of properly spaced trains of waves, a group of these constituting the elementary signal or *dot* of the Morse code.

For naval and war purposes the speed of transmission of a message is not nearly so important as its absolute privacy, and the impossibility of an enemy mutilating the record, or preventing the reception.

A great deal of information can be compressed into a single word

by the use of a code, but then the absolute accuracy of every signal becomes supremely important.

For this purpose, also, automatic sending by punched tapes has a great advantage. The message can be punched in sections and carefully read before being passed through the transmitter, and can be sent several times over with absolute accuracy as regards spacing and lettering.

It is a well-known fact that the majority of messages (90 per cent.) sent by submarine cable are in code, and often the change of a letter would involve serious or costly mistakes. Hence, although hand sending and ear reception by telephone have great advantages for the ordinary conversational or even press news messages, there can be no doubt but that for the transmission of commercial messages on which financial results depend, accuracy is the more important quality, and no matter what the speed or distance, confidence will not be obtained unless the communicators are assured by experience of the same degree of accuracy with wireless transmission as with submarine cable transmission generally.

When, however, we remember that submarine cable telegraphy has more than fifty years' experience behind it, whilst electric wave radio telegraphy has not yet fourteen, we may well take encouragement from the great progress of the latter to believe that still more important achievements are in store for the method of telegraphy by unguided electromagnetic waves.

23. Legislation on the Subject of Wireless Telegraphy.—The increasing importance of wireless telegraphy in connection with naval operations caused the principal maritime powers in the world to make it a subject of legislation between 1900 and 1904. In addition, the work of the Marconi Wireless Telegraph Company, in organizing a splendid system of inter-communications between ships at sea and the shore, and its increasing importance, naturally drew the attention of other nations to the commercial value of this form of telegraphy.

With the professed object of increasing these public facilities, the German Government called an International Conference on the subject of wireless telegraphy in 1903, which commenced its sittings in the Imperial Post Office at Berlin, in August, 1903. Representatives from the European Powers and the United States were invited to assemble and discuss the subject of International Legislation of Wireless Telegraphy, with the ostensible purpose of eliminating special interests and developing the art for the common benefit of seafaring people.

At this Conference, representatives of Great Britain, the United States, France, Germany, Italy, Austria-Hungary, Russia, and Spain, were in attendance, and the secretary of the German Post Office opened the proceedings.

The German proposals were then laid before the Conference by Herr Sydow, Under-Secretary of the Post Office. The motive which prompted the issuance of an invitation to this Conference on the part of the German Government was undoubtedly the desire to prevent, if possible, a ship to shore telegraphy from falling entirely into the hands of a single corporation or country.

The Marconi Wireless Telegraph Company of England, formed to

conduct and apply commercially Mr. Marconi's inventions, was naturally not administered on purely altruistic principles, but being a commercial organization, and having made a large expenditure of its shareholders' money in bringing these inventions into a condition in which they could become commercially remunerative, looked for an adequate return on the capital so expended. By skilful management and wise prevision, they had entered into contracts with foreign and Colonial Governments, as well as with the Corporation of Lloyds, the result being to build up a splendid organization securing the utmost possible facility and unity for maritime communications by means of electric wave wireless telegraphy.

The German Government were anxious to secure that all wireless telegraph messages to and from ships should be taken and transmitted without distinction of systems, that is to say, that a Marconi coast installation, say in England, or on a ship at sea, should be bound to send messages to, or accept messages from, a ship equipped with German apparatus. Such a free use, however, of the Marconi system and organization by foreign competitors would no doubt have been very advantageous to them, but it does not follow that the public interests would have been better served, whilst a grave injustice would have been done to those who had borne the burden of creating the system and appliances necessary for bringing this invention into practical use.

The result of the Conference was that the majority of the representatives of the European Powers adopted two resolutions, which it was hoped might afford a basis for a further conference. These were as follows:—

1. The coast stations should be obliged to receive and transmit all telegrams from and to ships at sea, without respect to the system, in order to facilitate communication between the ships and stations. As far as possible, all necessary technical information as to their equipment should be published. It should be the duty of these stations to give precedence to telegrams relating to shipwrecks and appeals for help for ships. It is further provided that the States in question should fix a tariff for forwarding communications which should be based on the tariff now in force for ordinary telegrams, plus a special charge for the use of wireless telegraph telegrams, the latter charge fixed at such a figure that the due remuneration is paid for the services of wireless telegraphy. Tariffs shall in all cases be based on the number of words. The rates are to be fixed with the consent of the company on which the land stations are, or the country whose flag is carried by the ships' stations.

2. In other respects it is provided that the wireless telegraph service shall be so regulated that the individual stations disturb one another as little as possible.

A number of technical provisions were also made, intended to secure the best and most profitable working of wireless telegraphy.

A protocol agreeing with the above resolutions was signed by representatives of Germany, Austria-Hungary, Spain, United States, France, and Russia. The United States pointed out, however, that American law would prevent the Government from forbidding the company to erect a signalling station because that company refused

to exchange telegrams with stations in another country equipped with a different system.

Great Britain and Italy took up a different position. The Italian Government having already entered into an agreement with Mr. Marconi to use his system exclusively for fourteen years, and not to exchange telegrams with stations equipped with other systems, the Italian delegates were consequently prevented from agreeing to the above resolution or to that part of it which would be in contravention with this agreement.

The British delegates intimated that they would lay the results of the preliminary Conference before their Government; they took exception particularly to the first article of the protocol.

Although it was intended that this Conference should be the precursor of another, yet it is clear that German diplomacy has not been entirely successful in bringing about the desired result as a consequence of this preliminary Conference.

In the year 1904 the British Government felt the importance of controlling by legislation the use of wireless telegraphy, so that irregular or nefarious operations might be prevented. An Act was accordingly passed through the two Houses of Parliament and received the Royal Assent in August, 1904, entitled "An Act to provide for the Regulation of Wireless Telegraphy" (August 15, 1904).

In this Act (see Appendix I.) it was provided that no person should establish or work a wireless telegraph apparatus in Great Britain or on a British ship except under licence from the Postmaster-General. Licences were to be granted either for commercial purposes or ship to shore communications, or else under regulation for purely experimental purposes. It was furthermore decreed that this Act should continue in force until July, 1906, and no longer, unless Parliament otherwise determines.

In February, 1906, an Amendments Act was passed, extending the operation of the Act of 1904 for a further six years.

In 1906 the German Government again issued an invitation to all the Powers to meet a second time in conference at Berlin and discuss an International Convention on wireless telegraphy. This Conference commenced its sittings in October, 1906, and was attended by representatives of the following Governments: Argentina, Austria-Hungary, Belgium, Brazil, Bulgaria, Chili, Denmark, Egypt, France, Germany, Greece, Great Britain, Italy, Japan, Mexico, Monaco, Montenegro, Netherlands, Norway, Persia, Portugal, Roumania, Russia, Siam, Spain, Sweden, the United States, and Uruguay.

The Conference had before it for consideration the text of a convention providing regulations for the international control of radiotelegraphy, which was discussed article by article. The chief discussion turned round Article 3, which provided that coast stations and ship stations are to be bound to exchange radiotelegrams regardless of the system used in them. Other articles dealt with the definition of wave lengths to be employed for particular services and regulations of working, and also with the creation of an International Bureau for collecting and diffusing information. The Convention having been provisionally agreed to by the representatives of the several Powers with certain modifications, it was referred to

the respective Governments for ratification. Objections were raised in Parliament to ratification by the British Government, and the House of Commons thereupon appointed a Select Committee to report to it on the recommendations of the International Berlin Conference of 1906. This Committee commenced its sittings in April, 1907, under the Chairmanship of Sir John Dickson-Poynder. Evidence was offered for and against ratification by Government officials, representatives of the Marconi Company, and others concerned. This Committee drew up a report, which was issued in November, 1907, as a Parliamentary Blue-book.

By a majority of one in a Committee of eleven members they recommended ratification on behalf of the British Government. This ratification took effect on and from July 1, 1908.

The text of the agreed International Service regulations is given in Appendix II.

In September, 1909, an agreement was made between Marconi's Wireless Telegraph Company and the Marconi International Marine Communication Company and the Postmaster-General, whereby in consideration of the sum of £15,000 the Companies transferred to the Post Office certain Coast Stations which from January 1, 1910, were taken over and worked by the British Post Office (see *The Electrician*, vol. 64, p. 639, January 28, 1910).

CHAPTER VIII

THE APPLIANCES OF ELECTRIC WAVE TELEGRAPHY

1. General Principles of Electric Wave Telegraphy.—In the previous chapter we have seen that electric wave telegraphy is based upon the production of controlled trains of Hertzian waves, created in the æther at some generating station, and propagated in the space above the surface of the earth in all directions round the radiator. This effect can be detected at a distance by means of appliances collectively described as wave detectors or cymoscopes when associated with a receiving antenna, and can be so controlled as to be interpretable in the form of intelligible signals. These signals are made on the universally accepted Morse International Code, and consist of two signs, one called a *dot* and the other a *dash*, grouped in various ways to form letters, words, and numbers. The telegraphic alphabet as employed in the British Postal Telegraph Service and also in wireless telegraphy is the International Morse Code as follows. The unit is the *dot signal*, which may either consist in a short mark made on a strip of paper, Morse telegraphic tape, or a short sound, tick, or buzz made by a telephone or a brief deflection of a galvanometer needle or spot of light. A *dash signal* is a longer mark, sound, or deflection, equal in magnitude or duration to three dots. A *dot space* is a blank equal in duration to a dot, left between the signs forming a letter, and a *dash space* is a blank equal in duration to a dash left between letters forming a word. A space equal to five dots is allowed between words, and a longer space between sentences.

The following signs form the code :—

THE INTERNATIONAL MORSE ALPHABET.

A	· —	N	— ·
B	— · · ·	O	— — —
C	— · — ·	P	· — — ·
D	— · ·	Q	— — · —
E	·	R	· — ·
F	· · — ·	S	· · ·
G	— — ·	T	—
H	· · · ·	U	· · —
I	· ·	V	· · · —
J	· — — —	W	· — —
K	— · —	X	— · · —
L	· — · ·	Y	— · — —
M	— —	Z	— — · ·

THE NUMERALS.

1	– —— —— —— ——	6	—— – – – –
2	– – —— —— ——	7	—— —— – – –
3	– – – —— ——	8	—— —— —— – –
4	– – – – ——	9	—— —— —— —— –
5	– – – – –	0	—— —— —— —— ——

SIGNS.

Understand – – – —— –

Repeat – – —— —— – –

Go on —— —— –

Wait —— ——   —— —— – ——

Call signal – – – ——

A full stop – –   – –   – –

A hyphen —— – – – – ——

An apostrophe – —— —— —— —— –

If, therefore, the trains of electric waves sent out from the transmitting station can be controlled as to the duration of their groups, that is to say, a greater or less number of groups of wave trains sent out, and if these can be made to influence for a longer or shorter time some recipient device giving visible or audible signals of corresponding duration, we have the means of transmitttng the words of any language which is alphabetic.

In the case of Chinese, Japanese, and other non-alphabetic languages, the ideographs can be numbered, and the numbers transmitted and then translated.

Generally speaking, if the signal made at the receiving end is visual, the receiver is called telegraphic, but if it is audible and heard in a telephone, the reception is called telephonic. There is no true scientific distinction between the two methods; the telephone when used in this manner is a telegraphic instrument of a particular kind, making an audible signal, just as a buzzer or Bright's bell are other forms.

The signals can, of course, be sent in ordinary conversational words or in code words, and by far the larger portion of all commercial and naval intelligence is transmitted by special code. There are considerable advantages in the reception of a message by some form of receiver which prints it down on paper tape, or records it by photography, as we then possess a record which subsequently can be critically considered, and any errors or obscurities in it perhaps rectified by experienced guessing, whereas the failure to receive

rightly a single letter or word on the telephonic method cannot be overcome in the same manner. On the other hand, the telephonic methods generally admit of greater speed, as the appeal is made directly to the ear, and the essential inertia or delay in the recording device is absent. In the same manner, automatic sending by means of punched tape has great advantages over ordinary hand sending, in speed, spacing, and accuracy. The most usual obstacle to intelligibility is bad spacing in letters and words. Great precision is necessary to secure the perfect exactness in the time duration of the signs, sounds, or deflections which constitutes good sending on the Morse code. Moreover, each hand sender has his own peculiarities, and can be recognized by these, just as each individual has his own caligraphy. Hence the advantages of automatic sending by means of punched tape are considerable.

The transmitting apparatus involves the following elements :—

(i.) The radiator or antenna, including the earth plate or else the balancing capacity.

(ii.) The arrangements for producing the electric oscillations in the antenna, either intermittent or else persistent or undamped.

(iii.) The source of electromotive force or charging voltage.

(iv.) The key or controller for starting and stopping the oscillations.

At the receiving station the apparatus may be analyzed into—

(i.) The receiving antenna and earth plate or balancing capacity.

(ii.) The cymoscope or wave detector and associated oscillatory circuits.

(iii.) The recording or signal producing instrument.

Each wireless telegraph station is equipped with sending and receiving apparatus, whilst the antenna is usually common to both, and used for sending and receiving alternately, being switched over from the transmitter to the receiver as required, or it can be simultaneously used with the aid of special appliances.

We shall proceed to discuss some of the scientific questions involved in the working and construction of this apparatus.

2. The Aerial Wire or Antenna, its Construction and Support. —The simplest form of radiator or antenna is a single metallic wire upheld in a nearly vertical position by an insulator from a mast, tower, or chimney, the said wire being either bare or insulated. As regards material, tinned hard-drawn copper, silicon bronze, or aluminium wire, bare or else insulated with indiarubber, is generally employed. The wire may be solid or stranded, a stranded wire of tinned copper 7/20 or 7/22 S.W.G. being a convenient size. Bare iron wire cannot be used, as its magnetic qualities would damp out the oscillations too quickly. If, however, the iron is thickly galvanized, it may be employed on an emergency. The author has for a long time past made use of aluminium wire for antennæ. As the high frequency oscillations are entirely on the surface of the wire, specific resistance does not come in question. The only qualities of the aerial wire with which we are concerned, other than magnetic permeability, are tensile strength, durability, weight, and cost per pound or kilogramme. Since the specific gravity of aluminium is 2·7, and that of copper 8·9, a given size and length of copper wire will weigh rather more than three times that of a similar aluminium wire.

The tensile strength of pure aluminium is 5·27 tons per square inch, and that of hard copper is about 15 tons per square inch. Alloys of aluminium are, however, now prepared having nearly the same density as pure aluminium, but a tensile strength equal to that of hard-drawn copper. The prices of copper and aluminium per ton are at the present time not very different, copper being now (1910) £63 and aluminium £75 per ton. Hence an aerial wire of any given diameter and length in aluminium will both weigh and cost one-third of an equal-sized wire in copper. Experience has shown that if galvanic action is avoided by not making contact between it and other metals, aluminium will stand very well the action of town or sea air.

The author has had in use at University College, London, for many years, an aluminium aerial with satisfactory results, the cost and weight of which was much less than that of an equal-sized copper one.

In the case of large aerials the element of weight is important, and the use of aluminium or alloys of aluminium having a density not exceeding 3 and tensile strength not less than 20 tons per square inch, as material for the aerial wire, will be found advantageous.

The aerial wire has to be upheld in a vertical position, and the usual method is to suspend it from a mast or tower. In Marconi's earliest experiments he employed metal cans placed hat-wise upon wooden poles and connected by a wire with the oscillation producer. In his fundamental patent he describes metal plates suspended from wooden frames, and in some of his earliest demonstrations, as in his first transatlantic achievement, he employed kites and balloons to sustain the wire (see Fig. 1, Chap. VII.).

The next improvement was to erect a ship mast on shore and suspend the wire from a spit or gaff braced at the top. Marconi employed in his cross-channel work between England and France, in 1899, 150-feet masts in three sections, strongly stayed with hemp ropes. For his earliest work at Poldhu and Nova Scotia, 200-feet masts were erected, each put up in four sections, and a ring of such masts was used. The masts were supported by steel wire stays divided into sections by dead-eyes.

For the permanent Marconi power station at Poldhu in Cornwall, wooden lattice towers were erected, strongly cross-braced and stayed (see Fig. 17, Chap. VII.). J. J. Stone has suggested the use of metal lattice towers divided into sections by insulating material.[1] In some cases, as at the Nauen station in Germany, the tower is of metal, and is insulated at the lower end, and forms part of the radiator. In other places as at the Marconi station at Clifden, in Ireland, masts are employed.

In the case of ships or lightships, it is usual to add a gaff to the existing masts to gain greater height. In some cases two gaffs are used, and from a stay between the aerial wires suspended. This was done in the case of the Italian warship *Carlo Alberto*, placed at Mr. Marconi's disposal by the Italian Government for experimental purposes (see Fig. 18, Chap. VII.). In the case of battleships it is

[1] See J. J. Stone, British Patent Specification, No. 29,146 of 1904.

usual to add a special gaff or gaffs to the masts to secure greater height for the antenna.

The sufficient insulation of the aerial at the top is an important matter. It was at first customary to employ a simple ebonite rod attached to the gaff, from the lower end of which the wire was suspended. Later flanged and shielded ebonite rods have been employed. The author has designed and used for some time an effective form of insulator made as follows: A thick ebonite tube, E, has a recess turned out at the top (see Fig. 1). In the interior of the tube a brass rod, S, fits tightly, the upper end of which is formed like the head of a pin. This head lies in the cupped recess of the ebonite, and an ebonite plug, P, is then tightly fitted in with Chatterton's compound. The ebonite tube is gripped outside by a cross bar of oak, W, which carries also a brass suspension loop, L. The result of this construction is that the ebonite is under compressional and not tensional strain, and is able to stand a greater pull between the loop and eye of the pin.

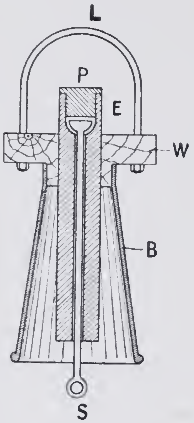


Fig. 1.—Antenna Insulator. (Fleming.) E, ebonite tube; P, ebonite plug; S, brass pin; W, oak cross bar; B, bell-shaped metal protector; L, suspension loop.

In addition, a wider metal tube, B, is fitted to a ring embracing the ebonite rod, and this tube is made water-tight at the upper end so that the metal tube acts as a petticoat to keep the ebonite rod dry. The lower end of the brass rod is formed into a loop to which the aerial wire is attached, and the ebonite

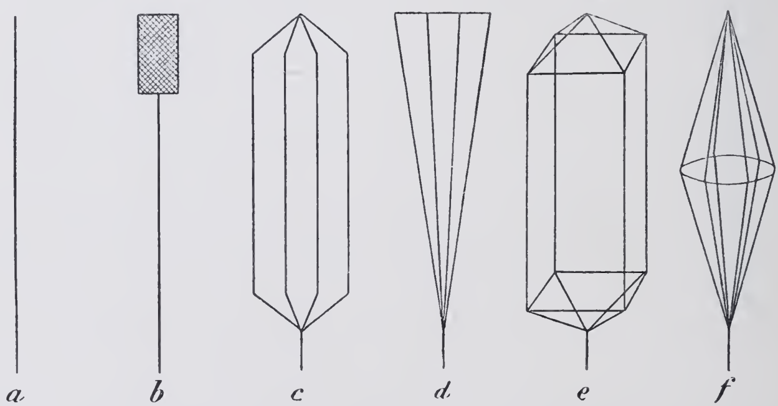


Fig. 2.—Various Forms of Antenna used in Electric Wave Telegraphy. *a*, plain aerial wire; *b*, wire with capacity plate at top; *c*, multiple wire antenna; *d*, fan-shaped antenna; *e*, cage or quadruple wire antenna; *f*, double cone antenna.

insulator is suspended from the gaff of the mast. In some cases a chain of two or three such insulators can be employed. The aerial

wire on board ship sometimes requires tying back to keep it clear of rigging, and in this case the tie-backs or stays must be connected to insulators of the above kind.

In place of a single wire antenna two or four wires may be employed, arranged in parallel and connected at the ends to the arms of a wooden cross.

Such multiple wire aerials may take several forms. They may take the form of parallel wire or cage-shaped or else fan-shaped conical or double-cone multiple wire aerials (see Fig. 2).

On British battleships and large liners the antenna now consists of a series of six or eight parallel wires, which are kept apart by star-shaped wooden separators. These sixfold antenna are stretched from mast to mast on insulators, and brought down also to the signalling cabin (see Fig. 3).

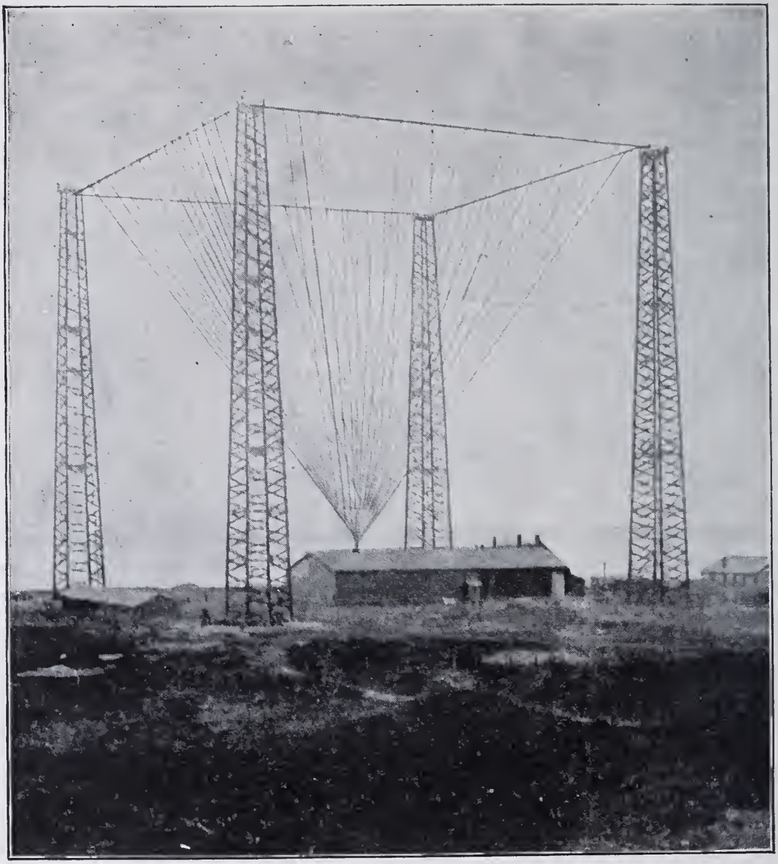
FIG. 3.—Star or Six-fold Antenna as used on British Battleships.

A cone-shaped antenna, consisting of a very large number of wires, was originally employed in the first large radio-telegraphic stations of the Marconi Company at Cape Breton, and at Cape Cod (see Fig. 4); but after the invention by Mr. Marconi of the bent or *directive antenna*, partly vertical and partly horizontal, these cone antennæ have been replaced by antennæ of the type shown in Fig. 5, which have the peculiar property of projecting radiation more strongly in the direction away from which the free end points. The theory and action of these forms of directive antennæ will be considered in a subsequent section (see § 5).

Lodge suggested a form of insulated roof antenna, in which a metal surface is carried on insulators placed on metal or wooden supports. An effective and much used form of antenna is the umbrella antenna, in which a number of nearly vertical wires have radial extensions from the top dipping downwards (see Fig. 6). The advantage of a multiple antenna is that it has a larger capacity, and therefore yields a longer wave length, than a single wire of the same length. In addition to this, the subdivision and separation of the mass of the antenna into separated portions greatly reduces the effective inductance, and so aids the increase of the antenna current.

In all cases the mast or tower has to be supported by stays, and if these are made of steel rope, as is generally the case, they must be cut up into sections by means of insulators, so that they are not of nearly the same length as the antenna wires themselves, or, in other words, are much out of tune with the antenna wires considered as electrical oscillators. If this is not done and if the stay wires happen to have a natural period of electrical oscillation near to that of the waves for which that particular station is tuned, they would absorb a good deal of the energy of these waves and so diminish the amount available for absorption by the true antenna.

In many cases complex antenna are employed, consisting of two or more antenna joined, it may be, at the bottom or at the top, or with the free ends approximated, thus forming a more or less closed circuit forming a triangular or loop antenna (see Fig. 7).



From "The Electrician."

FIG. 4.—Marconi Power Station at Cape Breton, Nova Scotia, for Electric Wave Telegraphy, showing the Antenna Wires as at first arranged in the form of a Square Cone upheld by Wooden Lattice Towers.

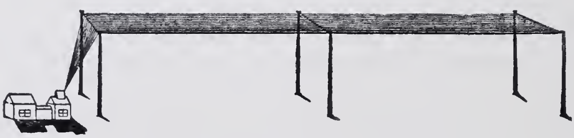


FIG. 5.—Marconi's Bent or Directive Antenna.

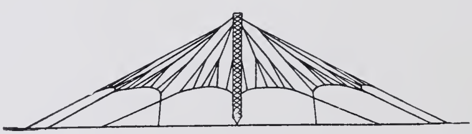


FIG. 6.—Umbrella Antenna.

3. Classification of Antennæ. Open and Closed Circuit Antennæ.—The various forms of antennæ used may be classified according to certain definite principles. We have first the general but ill-defined distinction between open and closed antennæ already mentioned.

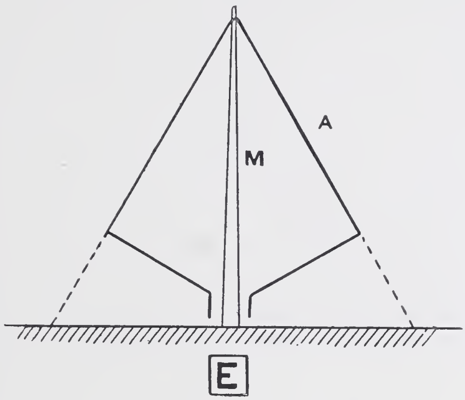


Fig. 7.

The typical open circuit antenna is a straight wire insulated at the upper end and upheld so as to stand nearly vertically to the earth's surface. In it electric oscillations can be set up either by charging the wire and suddenly discharging it to earth, as in the original Marconi method, or by connecting it directly or inductively to a syntonic nearly closed energizing circuit in which oscillations are established by the arc or spark method.

This open oscillator is characterized by a perfect spacial symmetry. The magnetic field round it is distributed in circles with their centres on the wire (see Fig. 8) and the lines of electric force lie in radial planes intersecting on the wire as shown in Chap. V. § 7. Hence it radiates strongly and equally in all directions. It has therefore a

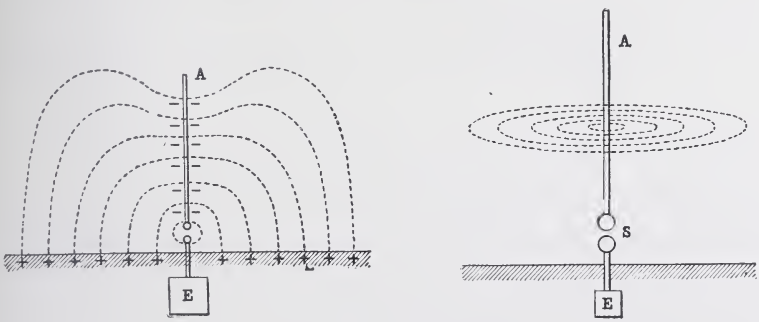


Fig. 8.

Lines of Electric Force of Linear Antenna.

Lines of Magnetic Force of Linear Antenna.

large radiation decrement, and its oscillations will be damped out quickly unless energy is continually supplied to it from an energizing circuit. Such an oscillator is frequently called an *electric oscillator.* In comparison with this, at the other extreme we have the closed or *magnetic oscillator*, in which a nearly closed conductive circuit is interrupted by a condenser with plates near together and at most by a short spark gap (see Fig. 9). In this case the magnetic field is only symmetrical with regard to the plane of the oscillator but not

with regard to a vertical line. If we suppose such a closed oscillator placed with its plane vertical and to be traversed by a current, then if at any instant the current is flowing round it counter-clockwise the internal magnetic field will be directed towards the spectator and the lines will double back and outside the circuit will be directed away from the spectator, thus completing their circuit (see Fig. 10). If we represent the section of a magnetic line of force by a small circle, we can put a dot in the circle to indicate that the direction of the force is towards the reader and a cross if it is away from the reader, and in the diagram in Fig. 10 the direction is so indicated for the instant when the current in the antenna is in the counter-clockwise direction. A closed circuit when traversed by a high frequency current or oscillation gives rise not only to magnetic but to electric force in the external space and radiates electromagnetic waves. We have already obtained (see § 13, Chap. V.) expressions for the electric and magnetic forces of the closed or magnetic oscillator and for the radiation from it, hence these need not be repeated. But from the remarks there made as to the form of the electric and

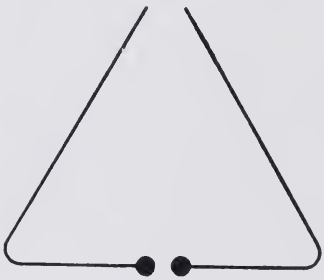


Fig. 9.—Nearly closed Triangular Antenna.

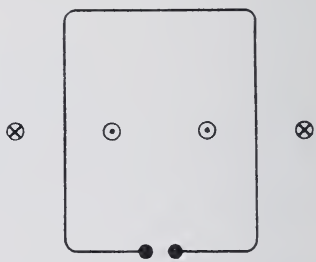


Fig. 10.—Diagram illustrating the disposition of the Magnetic Field of a Closed Antenna.

magnetic field of the closed oscillator it will be evident that its radiation is a maximum in the plane of the oscillator.

To sum up, we may say that although the closed circuit antenna has generally less radiative power and less radiation decrement than the open circuit antenna, yet it has a certain asymmetry of radiation which gives it importance and utility in radiotelegraphy. Again, we have many different types of antenna intermediate between the straight, vertical open circuit antenna and the completely closed antenna, which possess in intermediate degree the useful qualities of both open and closed antenna.

Hence certain forms of antennæ may be regarded as combinations of the open or electric, and closed or magnetic oscillator.

4. Bent or Inclined Antennæ.—A theory of the operation of bent or inclined antennæ may be based upon the assumption that they may be regarded as equivalent to the conjunction of an open or electric oscillator and a completely closed or magnetic oscillator. Consider, for example, a square or rectangular circuit ABCD (see Fig. 11), in which electric oscillations are taking place. The magnetic field of such an oscillator consists of closed lines which embrace the

circuit of the oscillator. These lines are all perpendicular to the plane ABCD in crossing that plane, and if the current is in any instant going round in the same direction to the hands of a watch, that is, in the direction ABDC, the lines of magnetic force in the included space are proceeding away from the reader, and returning on all sides outside the area towards the reader.

In Fig. 11 the small circles represent the section of a pair of such lines of magnetic force outside the oscillator returning back on both sides in the equatorial line by the two little circles marked + H, in which the magnetic flux is towards the reader. On the other hand, if we consider a simple open antenna EF of the same height as the side of the rectangle BD, and consider the nature of the magnetic force round it when a current is flowing upwards in it, it will be seen that these lines are circles lying in planes at right angles to the antenna, and that the sections of these lines in that plane may be represented by the little circles $+ h'$ and $- h$, marked respectively with a dot and a cross. If, then, we suppose the open and closed circuits to be

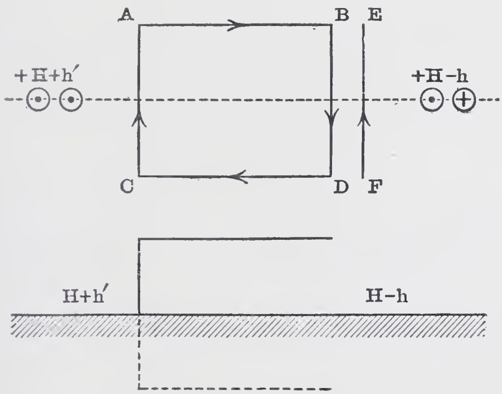


Fig. 11.

placed so that the open one is in close contiguity to one side of the closed one (see upper diagram of Fig. 11), and that the oscillations in these parts of the two circuits in contiguity are always in opposite directions, then it is quite easy to see that the field due to the open circuit antenna will assist the field due to the closed circuit antenna on the left-hand side, but tend to weaken it on the right-hand side. So that if we call the field due to the open antenna on the one side h, and on the other side h', the resultant field due to the combined open and closed antennæ will be $\mathrm{H} + h'$ on the left-hand side, $\mathrm{H} - h$ on the right-hand side.

We can now imagine the two oscillations in the continuous wires BD, EF which are opposed in direction to annihilate each other, and the result is that we are left with a bent antenna as in the lower diagram of Fig. 11, in which if oscillations are set up we are able to produce a field which is non-symmetrical, being greater on the side away from which the open ends point. Such an antenna is called a bent antenna, and if we imagine it half buried in the earth, the

surface of the earth being a plane of zero potential, it produces the same effect above the earth's surface as one-half of a complete double bent antenna. It follows, then, that an earthed antenna partly vertical and partly horizontal must produce a non-symmetrical radiation.

The author has given an analytical discussion of the theory of a bent antenna, based on the above view that it could be considered as composed of the superposed Hertzian oscillators. (See J. A. Fleming, *Proc. Roy. Soc. Lond.*, ser. A., vol. 78, p. 1. 1906. A note on the theory of Directive Antennæ, or Unsymmetrical Hertzian Oscillators.)

The analytical treatment of the subject presents, however, enormous difficulties unless we limit consideration to the case in which the current in the oscillator is assumed to have the same value at all points at the same time, and also that the dimensions of the oscillator are small compared with the distance from it of the points at which the field is considered. The first assumption is not strictly true for any ordinary radiotelegraphic antenna, but is necessary to bring the case under mathematical treatment.

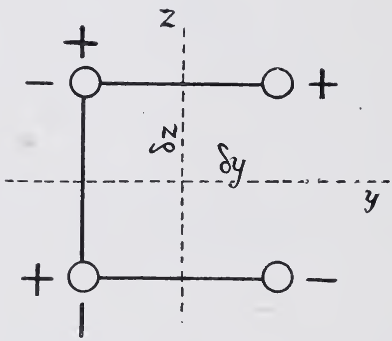


FIG. 12.

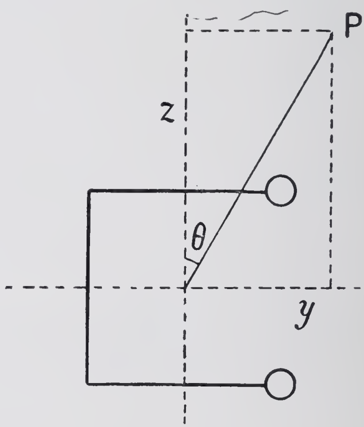


FIG. 13.

One form of bent oscillator of the above kind may be considered to be made up by the superposition of three Hertzian electric oscillators placed at right angles to each other, the poles being so arranged that at the two corners poles of opposite signs are superimposed, the oscillations in all being synchronous and similarly directed (see Fig. 12). Hence, to obtain the field of the bent oscillator, we need merely to calculate those of the components and add them together.

Let a single electric oscillator be placed with its centre at the origin and axis coinciding with the z axis. Let oscillations exist in it of period $2\pi/n$ and radiation be emitted of wave length $2\pi/m$. Suppose the length of the oscillator to be denoted by δz, the electric charge at either pole at any instant by q, the uniform current in the axis by i, whilst Q and I are the maximum values of q and i which vary so that $q = \mathrm{Q} \sin nt$ and $i = \mathrm{I} \cos nt$. Also let $\phi = \mathrm{Q}\delta z$ be the maximum electric moment of the oscillator. We have, therefore, $\mathrm{I} = \mathrm{Q}n$ or $\phi n = \mathrm{I}\delta z$, and $n/m = v$, the velocity of propagation of the

radiation through space. The scalar potential V at any point P whose distance from the origin is r, is given by

$$V = -\frac{\phi}{k}\frac{d}{dz}\left(\frac{\sin(mr - nt)}{r}\right) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where k is the dielectric constant of the medium, and $r^2 = x^2 + y^2 + z^2$.

Also, if F, G, and H are the components of vector potential at P, we have in this case F = G = 0, and

$$H = -I\delta z\frac{\cos(mr - nt)}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If, as before, we employ the symbol Π to stand for

$$\frac{\sin(mr - nt)}{r}$$

we can write the above expressions (1) and (2) in the form

$$V = -\frac{\phi}{k}\frac{d\Pi}{dz}, \qquad H = \phi\frac{d\Pi}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If we suppose this doublet to be moved parallel to itself in the negative direction so that its centre is displaced by a distance $-\frac{1}{2}\delta y$, the scalar and vector potentials at P become—

$$V = \left(-\frac{\phi}{k}\frac{d\Pi}{dt}\right) + \frac{1}{2}\frac{d}{dy}\left(\frac{\phi}{k}\frac{d\Pi}{dt}\right)\delta y \quad . \quad . \quad . \quad . \quad (4)$$

$$H = \phi\frac{d\Pi}{dt} - \frac{1}{2}\frac{d}{dy}\left(\phi\frac{d\Pi}{dt}\right)\delta y \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Consider, then, two other similar doublets of length δy, and maximum moment ϕ', placed with poles pointing in opposite directions and axes parallel to the axis of y, the doublets having centres at distances $+\frac{1}{2}\delta z$ and $-\frac{1}{2}\delta z$ from the origin and poles arranged as in Fig. 12. The scalar and vector potentials at the point P of these last two doublets constituting together a double-doublet are obviously given by

$$V = -\frac{\phi'}{k}\frac{d^2\Pi}{dz\,dy}\delta z \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$G = \phi'\frac{d^2\Pi}{dz\,dt}\delta z \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Hence, if three such short, straight oscillators, having equal currents and charges, are placed round the origin so as to create a doubly-bent oscillator, the scalar and vector potentials of this oscillator at a point P (see Fig 13), the distance of which from the origin is large compared with the linear dimensions of the oscillator, are given by

$$V = -\frac{\phi}{k}\frac{d\Pi}{dz} + \frac{1}{2}\frac{\phi}{k}\frac{d^2\Pi}{dy\,dz}\delta y - \frac{\phi'}{k}\frac{d^2\Pi}{dz\,dy}\delta z \quad . \quad . \quad . \quad (8)$$

$$\left.\begin{aligned} F &= 0 \\ G &= \phi'\frac{d^2\Pi}{dz\,dt}\delta z \\ H &= \phi\frac{d\Pi}{dt} - \frac{1}{2}\phi\frac{d^2\Pi}{dy\,dt}\delta y \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where $\phi'\delta z = \phi\delta y$.

The electric and magnetic forces at the point P, of which the axial components are X, Y, Z, and α, β, γ, can be obtained from equations (8) and (9) at once by the aid of the relations—

$$\left.\begin{aligned} X &= -\frac{dF}{dt} - \frac{dV}{dx} & \alpha &= \frac{dH}{dy} - \frac{dG}{dz} \\ Y &= -\frac{dG}{dt} - \frac{dV}{dy} & \beta &= \frac{dF}{dz} - \frac{dH}{dx} \\ Z &= -\frac{dH}{dt} - \frac{dV}{dz} & \gamma &= \frac{dG}{dx} - \frac{dF}{dy} \end{aligned}\right\} \quad . \quad . \quad . \quad (10)$$

For the present purposes we require only the electric and magnetic forces perpendicular to the radius vector r, taken at its extremity, when that radius is taken in the plane xy, which is normal to the plane yz in which the oscillator is situated. Hence we need only calculate the value of Z, α, and β for the case in question.

If we write M for $I\delta y\delta z$ and call this the magnetic moment of the bent oscillator, so that $\phi\delta y = \phi'\delta z = M/n$, we have the following equations for the potentials and forces in the field at points not very near the oscillator—

$$\left.\begin{aligned} V &= -\frac{\phi}{k}\frac{d\Pi}{dz} + \frac{\phi}{2k}\frac{d^2\Pi}{dy\,dz}\delta y - \frac{\phi'}{k}\frac{d^2\Pi}{dz\,dy}\delta z = -\frac{\phi}{k}\frac{d\Pi}{dz} - \frac{M}{2kn}\frac{d\Pi}{dy\,dz} \\ G &= \phi'\frac{d^2\Pi}{dz\,dt}\delta z = \frac{M}{n}\frac{d^2\Pi}{dy\,dt} \\ H &= \phi\frac{d\Pi}{dt} - \frac{\phi}{2}\frac{d^2\Pi}{dy\,dt^2}\delta y = \phi\frac{d\Pi}{dt} - \frac{M}{2n}\frac{d^2\Pi}{dy\,dt} \\ Z &= -\phi\frac{d^2\Pi}{dt^2} + \frac{M}{2n}\frac{d^3\Pi}{dy\,dt^2} + \frac{\phi}{k}\frac{d^2\Pi}{dz^2} + \frac{M}{2kn}\frac{d^3\Pi}{dy\,dz^2} \\ \alpha &= \phi\frac{d^2\Pi}{dy\,dt} = \frac{M}{2n}\frac{d^3\Pi}{dy^2\,dt} - \frac{M}{n}\frac{d^3\Pi}{dz^2\,dt} \\ \beta &= -\phi\frac{d^2\Pi}{dx\,dt} + \frac{M}{2n}\frac{d^3\Pi}{dx\,dy\,dt} \end{aligned}\right\} \quad (11)$$

Performing the necessary differentiations on the function

$$\Pi = \frac{\sin(mr - nt)}{r}$$

and collecting terms in $\sin(mr - nt)$ and $\cos(mr - nt)$, which for shortness will be written $\sin\chi$ and $\cos\chi$, also putting v for n/m or $(\mu k)^{-\frac{1}{2}}$, where μ and k are the permeability and dielectric constant of the medium, we have the following expressions for Z, α, and β:—

$$\begin{aligned} Z = &\Big\{\phi(m^2r^2 - 1) - \phi(m^2r^2 - 3)\left(\frac{z}{r}\right)^2 + \frac{M}{2v}\frac{3}{mr}\left(\frac{y}{r}\right) \\ &+ \frac{M}{2v}\frac{(6m^2r^2 - 15)}{mr}\left(\frac{y}{r}\right)\left(\frac{z}{r}\right)^2\Big\}\frac{\sin\chi}{kr^3} \\ &+ \Big\{\phi mr - \phi\, 3mr\left(\frac{z}{r}\right)^2 - \frac{M}{2v}(m^2r^2 + 3)\left(\frac{y}{r}\right) \\ &+ \frac{M}{2v}(15 - m^2r^2)\left(\frac{y}{r}\right)\left(\frac{z}{r}\right)^2\Big\}\frac{\cos\chi}{kr^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12) \end{aligned}$$

$$\alpha = \left\{\phi v m^2 r^2\left(\frac{y}{r}\right) + \frac{M}{2} 3mr\left(\frac{y}{r}\right)^2 - \frac{M}{2} 3mr + 3Mmr\left(\frac{z}{r}\right)^2\right\}\frac{\sin\chi}{r^3}$$
$$+\left\{\phi v m r\left(\frac{y}{r}\right) - \frac{M}{2}(m^2r^2-3)\left(\frac{y}{r}\right)^2 - \frac{3M}{2}\right.$$
$$\left. - M(m^2r^2-3)\left(\frac{z}{r}\right)^2\right\}\frac{\cos\chi}{r^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

$$\beta = -\left\{\phi v m^2 r^2\left(\frac{x}{r}\right) + \frac{M}{2} 3mr\left(\frac{x}{r}\right)\left(\frac{y}{r}\right)\right\}\frac{\sin\chi}{r^3}$$
$$-\left\{\phi v m r\left(\frac{x}{r}\right) - \frac{M}{2}(m^2r^2-3)\left(\frac{x}{r}\right)\left(\frac{y}{r}\right)\right\}\frac{\cos\chi}{r^3} \quad . \quad . \quad (14)$$

Suppose we limit attention to the value of the electric force e and the magnetic force d at right angles to the extremity of the radius vector r, the former being parallel to the z-axis and the latter being drawn in the plane of xy. The magnetic force d in this direction is equal to $\alpha y/r - \beta x/r$. Hence we obtain its value by multiplication of the values of α and β by y/r and x/r and subtraction. Then putting $z = 0$ in the above equations and writing $\cos\psi$ for y/r we have

$$e = \left\{\phi(m^2r^2 - 1) + \frac{M}{2v}\frac{3}{mr}\cos\psi\right\}\frac{\sin\chi}{kr^3}$$
$$+\left\{\phi mr - \frac{M}{2v}(m^2r^2+3)\cos\psi\right\}\frac{\cos\chi}{kr^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$d = \{\phi v m^2 r^2\}\frac{\sin\chi}{r^3} + \left\{\phi v m r - \frac{M}{2} m^2r^2\cos\psi\right\}\frac{\cos\chi}{r^3} \quad . \quad . \quad (16)$$

If we denote the amplitudes of e and d by E and D, we have finally

$$E = \frac{1}{kr^3}\sqrt{\left\{\phi(m^2r^2-1)+\frac{3}{2}\frac{M}{v}\frac{\cos\psi}{mr}\right\}^2 + \left\{\phi mr - \frac{M}{2v}(m^2r^2+3)\cos\psi\right\}^2} \quad (17)$$

$$D = \frac{1}{r^3}\sqrt{(\phi v m^2r^2)^2 + (\phi v m r - \frac{M}{2}m^2r^2\cos\psi)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where E is the amplitude of the electric force perpendicular to the radius vector and to the equatorial plane, and D is the amplitude of the magnetic force perpendicular to the radius vector and in the equatorial plane.

Hence, since m^2r^2 is always much greater than $1/mr$, it is clear that when ψ is 180° the values of E and D are both greater than when $\psi = 0°$.

If we put $M = 0$ in the above equations they reduce to the values given by Hertz for the electric and magnetic forces of the short straight oscillator or doublet taken in the equatorial plane, the electric force being parallel to the axis and magnetic force at right angles. When mr is large compared with unity we have $kE^2 = \mu H^2$, showing that the energies of the magnetic and electric components of the wave then become equal. Also there is a minimum value of D and E corresponding to a value of ψ such that

$$\cos\psi = \frac{2\phi v}{M}\frac{1}{mr}, \quad \text{or} \quad \cos\psi = \frac{2\phi v}{M}\frac{mr}{m^2r^2+3} \quad . \quad . \quad (19)$$

The above expressions are numerically small when r is large compared with the wave length of the radiation. Hence a minimum value of the forces at the extremity of the radius vector is found, corresponding to some azimuthal angle ψ rather less than 90° reckoned from the direction in which the free ends of the bent oscillator point.

The degree of this fore-and-aft inequality in the plane of the oscillator will depend upon the ratio of the magnitude of the quantities $\frac{1}{2}\mathrm{M}mr$ and ϕv or upon the ratio of δy to $2/m^2r$, that is upon the ratio of

$$\frac{\delta y}{\frac{1}{2}\delta z + \delta y} \quad \text{to} \quad \frac{4}{m^2 rl}, \quad i.e. \text{ to} \quad \frac{\lambda}{\pi^2 rl},$$

where $2l$ is the total length of the bent oscillator. The greatest inequality between the fore-and-aft radiation in the plane of the oscillator will exist when π^2 times the ratio of the sum of the lengths of the two horizontal parts of the oscillator to its total length is as nearly as possible equal to the product of the ratios of λ^2/l^2 and l/r. The ratio λ/l is fixed by the geometrical form of the oscillator, hence the inequality in radiative power in the fore-and-aft directions for a given oscillator essentially depends upon the ratio of wave length to the distance of the point at which observations are made, and at large distances will only be sensible when long wave lengths are employed.

The above theoretical examination of this operation of a bent oscillator shows clearly that its unsymmetrical radiation in the equatorial plane depends not upon absolute wave length, but upon the ratio of wave length to the distance of the receiving point and upon the proportion between the length of the vertical and of the horizontal portions of the oscillator.

The reader may also be referred to a paper by Professor H. M. Macdonald, F.R.S., entitled, "A Note on Horizontal Receivers and Transmitters in Wireless Telegraphy," *Proc. Roy. Soc. Lond.*, vol. 81, A., p. 394, 1908.

The above investigation shows that if an antenna is bent or inclined so that it is partly vertical and partly horizontal, the result is to produce a non-symmetrical radiation; in other words, to give the antenna a *directive* quality as regards radiation, and that this arises from the fact that such an antenna may be regarded as the result of a combination of the open and closed type. This property of the bent or inclined antenna was, however, not discovered by mathematical analysis, but experimentally in the endeavour to achieve the feat of directing radiotelegraphic waves.

Although the mathematical method of treating the problem of the bent antenna given in this section is based on ideas which are in accordance with experience, and is confirmed by the experimental work of Bellini and Tosi described below, it has been criticized by K. Uller and L. Mandelstam, who have taken exception to it on the ground that in the above formulæ (17) the algebraic sign prefixed to the second term inside each bracket should be changed, and $-$ M written for $+$ M. The author has, however, been unable to agree with this criticism; but for the detailed discussion of this difference of opinion the reader must be referred to the critical articles in the

Jahrbuch der Drahtlosen Telegraphie und Telephonie, vol. 1, pp. 291 and 333, 1908, and the author's reply on p. 329 of the same journal. Also for Uller's criticism to *Phys. Zeitschrift*, vol. 8, p. 193, 1907, or *Science Abstracts*, vol. 10, A., *abs.* 874, 1907. Another theory of the action of a sloping antenna has been put forward by J. Zenneck (*Phys. Zeitschrift*, vol. 9, p. 50, Jan. 15, 1908, or *Science Abstracts*, vol. 11, B., June, 1908, *abs.* 705).

He bases his explanation on the opinion, that at great distances from the transmitter the electrical field of the transmitted waves is, in general, an alternating field more or less inclined to the vertical, and having a rotating component, that is, there is always a horizontal component in addition to a vertical one. The effect in the receiving antenna is, then, due to the sum or difference of the component fields or forces according as the free end of the antenna points away from or towards the transmitting station.

This theory, however, offers no explanation of the figure-of-eight shape of the polar curve (see next section) given when the intensity of the antenna radiation is plotted out for various azimuths of the free end, whereas the theory given by the author as above does completely explain it.

5. **Directive Antennæ for Radiotelegraphy**.—At a very early stage in connection with radiotelegraphy the problem of directing the radiation, or concentrating it in certain directions, presented itself to inventors. The earliest attempts to give direction to an electric beam involved the use of parabolic mirrors. Hertz showed that electric waves could be reflected according to the same laws as rays of light, and in some of his earliest experiments he employed a pair of cylindrical parabolic mirrors for this purpose. In the focal line of one mirror a linear oscillator was placed, and in the focal line of the other a linear resonator. When the mirrors were placed in apposition, a beam of electric radiation was transmitted from one to the other, the beam being mostly confined to the space between the mirrors. In order that this experiment may succeed, it is necessary, however, to use radiation of a wave length which is small, or at least not large, compared with the dimensions of the mirror. Thus Hertz used cylindrical parabolic mirrors 12·5 cms. in focal length, which were about 2 metres high and 1 metre wide, and employed electric waves having a wave length of about 66 cms., or about 2 feet in length.[2]

In some of his earliest experiments on electric wave telegraphy, Marconi adopted the same plan, and used copper parabolic mirrors, by the aid of which he projected a beam of electric radiation in a certain direction for about 2 miles.[3]

In place of cylindrical parabolic mirrors, other inventors have proposed to employ vertical wires or rods arranged along a parabolic base line drawn on the ground, the radiator being placed in the focal line, *e.g.* S. G. Brown (see British Patent Specification No. 14,449, of 1899; also see U.S.A. Patent Specification of Lee de Forest, No. 748,597, of 1902).

[2] See Hertz, "Electric Waves," English translation by D. E. Jones, p. 175.
[3] See G. Marconi, "On Wireless Telegraphy," *Journal Inst. Elec. Eng.*, 1899, vol. 28, p. 282.

The devices are, however, unavailable when very long electric waves are employed. It is perfectly impracticable to construct mirrors of dimensions comparable in size with the length of electric waves of 500 or 1000 feet in wave length, and to employ smaller mirrors would be like attempting to conduct optical experiments with mirrors having dimensions of less than one hundred thousandth part of an inch.

A new line of investigation was, however, opened up by the observation that the radiation of a pair of antenna with currents in opposite directions, or of a sloping antenna, and particularly that of a vertical loop or nearly closed antenna, is non-symmetrical. In the British Patent Specification of S. G. Brown, No. 14,449 of 1899, a diagram is given showing a pair of vertical antennæ said to be separated by half a wave length, each attached to one of the spark balls of an induction coil. This arrangement is correctly stated to radiate and absorb best in the plane of the wires. It was also found that in the case of a closed loop it is greater in the plane of the loop than in any other plane. Observations concerning this phenomenon were made in 1898 and 1899 by S. G. Brown, by K. Strecker, and by A. Slaby, and in 1899 by J. Zenneck, and later by H. von Sigsfeld and by F. Braun in Germany.[4] Arrangements were also described in patent specifications by M. R. Garcia,[5] L. de Forest,[6] and J. S. Stone[7] for locating the direction of the transmitting station.

This pioneer work, however, did not sufficiently lead to practical achievement, whilst in some cases results said to have been obtained are clearly in contradiction with well-ascertained facts. In other cases there was no doubt a correct observation, but it was not followed up. Thus, L. de Forest states that an antenna formed of vertical and horizonal insulated rods with a spark gap placed at their junction is directive, and radiates more towards the side on which the vertical branch of the antenna is placed and in the plane of the antenna (U.S.A. Patent Specification, No. 749,131, applied for March 6, 1901).

The problem which seems first to have attracted attention was that of determining the direction of the transmitting station at the receiving station.

F. Braun states he had employed in 1903, as a means of so doing, a receiving antenna not horizontal, but sloping upwards at a small angle towards the incoming wave (see *The Electrician*, vol. 57, p. 247, 1906, and *Phys. Zeitschrift*, iv. p. 363, 1903).

Again, L. de Forest described in a United States Patent Specification an arrangement consisting of a metal plate or grid, longer in a horizontal than in a vertical direction, which is swivelled round a vertical axis so as to be capable of being oriented.[8] In the vertical part he places an electrolytic receiver of some kind shunted by a

[4] For a brief account of this early work on directive radiotelegraphy, the reader may be referred to an article in *The Electrician*, vol. 57, p. 220, May, 1906.

[5] See U.S.A. Patent Specifications of M. R. Garcia, No. 795,762, applied for January 10, 1901.

[6] See U.S.A. Patent Specifications of L. de Forest, No. 749,131, 1904, being a divided part of an original No. 720,568, March 6, 1901.

[7] See U.S.A. Patent Specifications of J. S. Stone, Nos. 716,134, 716,135, of 1902.

[8] See U.S.A. Patent Specifications of L. de Forest, Nos. 771,818, 771,819, applied for May 28, 1904.

telephone and local cell. He states that when the grid is placed broadside on to the incident waves it collects the largest amount of energy, and the oscillation detector is then most vigorously affected. Hence by rotating it round into this position the receiving operator can determine the direction of the radiant point. He states that with a collecting screen 15 feet by 6 feet in size, he has been able to locate within 10° the direction of a transmitting station 7 miles away. Another device by the same inventor consists in employing a horizontal antenna swivelled so as to rotate round a vertical portion, and in this is placed an electrolytic receiver of some kind shunted by a telephone and local cell. According to the specification, the horizontal portion may be extended in one or both directions, or may consist of a closed loop.

The inventor states that when turned round so that the direction of the horizontal part coincides with the direction of the incident waves, the oscillation detector in the vertical part gives its maximum indication and its minimum when the horizontal part lies transversely to the direction of motion of the signal waves.

J. S. Stone, following the prior suggestions of S. G. Brown (*loc. cit.*), proposed to place two vertical receiving antennæ at a distance apart equal to one half of a wave length of the waves employed, and to arrange these so as to be capable of rotating round an axis halfway between them. If, then, these two antennæ are placed in the line of direction in which the incident waves are travelling, the inventor states that they will be oppositely affected, and if the variations of potential or current at their respective bases are inductively combined so as to be added together, they will not affect a receiving instrument. On the other hand, if the line joining the two antennæ is perpendicular to the direction in which the waves are travelling, then the potential or current variations in them, being in the same phase, can be added together so as to affect a receiving instrument operated upon by the two antennæ jointly. Hence the direction in which the incident wave is travelling may be ascertained by finding the position in which the two receiving antennæ are *nil*. Apart, however, from the mechanical and almost insuperable difficulties of so dealing with antennæ, which must be hundreds of feet apart in the case of the waves used in electric wave telegraphy, this proposal neglects altogether the effects which arise from the damping in the wave train. When a wave train of highly damped electric waves is travelling through space, although the electric and magnetic forces at places separated by half a wave length are opposite in direction at any instant, they are not equal in magnitude. Accordingly, there would be a differential effect on the two antennæ placed half a wave length apart in the line of motion, due to the difference in magnitude of the simultaneous forces in opposite directions. Hence this plan of S. G. Brown and Stone, though ingenious and re-described subsequently by many other patentees, does not seem to have reached practical realization.

The first really practical solution of the problem, however, was obtained when Marconi made systematic observations of the radiation intensity in various directions, but at equal distances, round an antenna having a short part of its length vertical and a longer part

horizontal, combined with similar observations of the absorptive power of such an antenna in various directions.[9]

Setting up at one place such a bent transmitting antenna (see Fig. 14), Marconi took observations at equal distances around it, but in different azimuths, by means of a simple straight vertical receiving antenna, having in its circuit some form of quantitative oscillation

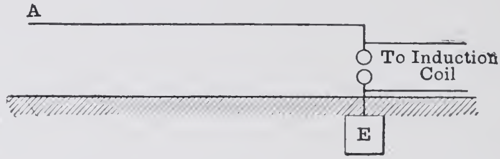


Fig. 14.—Marconi's Bent Transmitting Antenna for directing Electric Radiation.

detector, such as a Duddell thermal ammeter. The intensity of the radiation in any direction is then taken as proportional to the mean-square value of the currents read by the ammeter in the receiving circuit.

He set off these currents or intensities in a diagram as the radii of a polar curve (see Fig. 15), and obtained a closed curve something like a figure 8 with two unequal loops, the radii of this curve representing the intensity of the radiation for various angular directions round the bent transmitter. It was then seen that the radiation is greatest in one direction, and that is the direction away from which the free end of the bent radiator points. It is also a minimum in another direction approximately 110° from the maximum direction, and it has a secondary or intermediate minimum 180° in the opposite direction, that is, in the direction in which the free end of the bent antenna points. The shape of this curve can be fully accounted for theoretically, as shown in the previous section, by assuming that the bent antenna is a combination of a closed or magnetic oscillator and an open or electric oscillator.

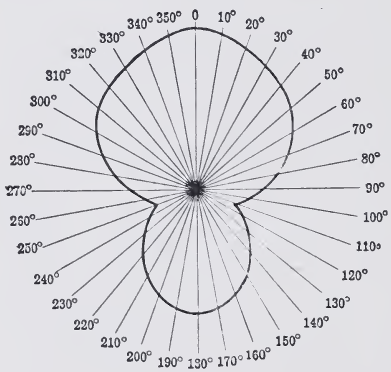


Fig. 15.—Polar Diagram showing the energy radiated by a Bent Antenna in Various Azimuths.

A large number of observations were thus obtained by Marconi with bent transmitting antennæ and vertical or open receiving antennæ, and also with vertical or symmetrical radiating antennæ and bent receiving antennæ placed in various relative positions, and these observations proved that an antenna which radiates best in any

[9] See G. Marconi, "On Methods whereby the Radiation of Electric Waves may be mainly confined to Certain Directions, and whereby the Receptivity of a Receiver may be restricted to Electric Waves emanating from Certain Directions," *Proc. Roy. Soc. Lond.*, Ser. A., vol. 77, p. 413. 1906.

one direction absorbs best, as a receiving antenna, waves which are coming from that direction, and also that when an antenna is constructed which is partly vertical and partly horizontal, the radiation is non-symmetrical, being greater in some directions than in others. Marconi's observations were made with radiating and receiving antennæ from 30 to 45 metres in length, separated by distances varying from about 250 metres to 600 or 700 metres, and he then found that for the same distance between the antennæ the intensity of the radiation, as measured by a thermal or magnetic oscillation detector, was sometimes as much as four times greater in the direction away from which the free end of the bent radiator pointed than in the same direction. The wave length of the waves used in his experiments was about 150 metres, and hence the maximum distance at which experiments were carried out was only about four or five wave lengths. Practical experience, however, shows that the same directive qualities exist at very much greater distances, but theory points to the fact that at extremely large distances the asymmetry tends to vanish, and that any bent oscillator, however arranged, has no asymmetry of radiation for very large distances. In one experiment he employed a horizontal wire 100 metres in length, placed at a slight distance above the earth's surface, and connected at one end through a spark gap with the earth. Such a transmitter sent out waves approximately 500 metres in length. The receiving antenna was a vertical wire 8 metres in length, tuned to the period of the transmitter by means of a syntonizing coil and connected to the earth through a magnetic oscillation detector. The signals were quite distinct at 16 kilometres when the horizontal part of the radiator pointed away from the receiver, but only very weak at 10 kilometres when the free end of the transmitter pointed towards the receiving wire, and quite undetectable at 6 kilometres when the free end of the transmitter pointed at right angles to the line joining the transmitter and receiver.

Again, at Clifden, Connemara, Ireland, by means of a horizontal conductor 230 metres in length as a receiving antenna, and connected to the earth through a magnetic oscillation detector, Marconi found it possible to receive with clearness all the signals transmitted from the Poldhu station at a distance of 500 kilometres, provided that the free end of the horizontal receiving antenna pointed directly away from the direction of Poldhu, whilst no signals at all could be received if the horizontal wire at Clifden made an angle of more than 35° with the line of direction of Poldhu. Furthermore, he found that he could receive signals from the Admiralty Station on the Scilly Isles at Mullion in Cornwall, a distance of 85 kilometres, by means of a horizontal receiving antenna 50 metres in length placed 2 metres above the ground, one end of the wire being connected to the earth through a magnetic oscillation detector, provided that the free end of the wire at Mullion pointed away from the Scilly Isles, but that no signals could be received if the horizontal portion was swivelled round so as to make an angle of more than twenty degrees with the line joining Mullion with Scilly.

It is an obvious consequence of the Law of Exchanges which holds good for electromagnetic radiation as well as for heat and

light, that any form of antenna which radiates better in one direction than another must absorb best radiation arriving from the direction towards which it radiates best.

Hence, by means of a horizontal wire 60 metres in length, supported 2 metres above the ground and connected at one end to the earth through a magnetic oscillation detector, Marconi was able to locate the direction of an invisible ship sixteen miles away, sending out electromagnetic waves, by noticing the direction in which the free end of the horizontal receiving antenna had to be placed in order to make the signals most strong. This direction was a direction opposite to that from which the waves were arriving.

Marconi employed, therefore, a pair of such bent antennæ (as in Fig. 16) as a means of achieving a practically useful directive telegraphy.[10]

He places a long horizontal insulated wire or wires parallel to the earth's surface, and at a distance from it small compared with the length of the wire. One end of this wire is insulated, and the other end is connected to an earth plate either through a pair of spark balls, if it is a transmitting antenna, or through an oscillation detector

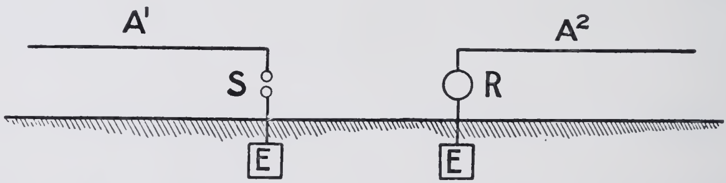


Fig. 16.—Marconi's Directive Antennæ for Electric Wave Direction Telegraphy. A^1, transmitting antenna; S, spark balls; A^2, receiving antenna; R, oscillation detector; E, earth plates.

of some form, if it is a receiving antenna. These antennæ, at the two stations (transmitting and receiving), are arranged back to back—that is, with their free or insulated ends pointing away from each other, but with the horizontal wires in the same vertical plane (see Fig. 16). In the diagram A^1 is the horizontal transmitting antenna and A^2 is the receiving antenna. The spark balls S are placed in the short vertical branch of the antenna A^1, and a receiving instrument, such as a magnetic detector, R, in the same number of the receiving antenna. The two earth plates are denoted by E. Marconi then found that the receiving instrument R is most strongly affected when the antennæ are placed as shown in Fig. 16, and with horizontal parts in one vertical plane. If, however, the receiving or transmitting antenna is turned round into any other position, the indications in the receiving instrument rapidly fall off in intensity; a variation of even 10° or 15° from alignment generally sufficing to render the signals insensible.

Some experiments of the same kind were made by the author in the same year (see *Phil. Mag.*, December, 1906, "On the Electric Radiation from Bent Antennæ," a paper read before the Physical Society of London, November 23, 1906, by J. A. Fleming). A vertical

[10] See British Patent Specifications of G. Marconi, No. 14,788, of July 18, 1905.

radiating antenna was employed consisting of a single wire which could be bent over at various heights from the ground, so as to make a bent antenna partly vertical and partly horizontal, the ratio of the horizontal to the vertical lengths being varied at pleasure. A vertical receiving antenna was employed at distances varying between 80 to 150 feet, and in the receiving antenna a hot-wire oscillation detector of the thermoelectric type, devised by the author, was employed to measure the R.M.S. value of the current created in the receiving antenna. The transmitting antenna had its horizontal part swivelled round in various directions at intervals of 15°, and in the several positions the current created in the receiving antenna was measured, the oscillations being excited in the transmitting antenna by means of a spark gap of constant spark length. The total length of the transmitting antenna was 20 feet, and the height of the receiving antenna was the same length.

The following Table shows the current in the receiving antenna in arbitrary units for each position of the horizontal part of the transmitting antenna.

Radiation from a Bent Earthed Transmitting Antenna 20 *feet in total length. Receiving Antenna vertical and* 20 *feet high. Distance between receiver and transmitter* 138 *feet.*

Length in feet of vertical part of Transmitter	5	4	3	2	1
Length in feet of horizontal part of Transmitter	15	16	17	18	19
Radiated wave length in feet	100	100	105	106	110
Azimuth of horizontal part of Transmitter.	Current in the receiving Antenna in arbitrary units.				
0	100	100	100	100	100
15	98	97	94	92	93
30	92	85	96	83	75
45	82	79	79	77	67
60	78	74	70	71	58
75	77	67	59	56	45
90	72	66	57	52	48
105	71	65	57	46	41
120	70	66	62	53	49
135	72	64	60	54	48
150	73	80	58	67	59
165	70	74	56	69	60
180	82	69	64	63	68

These observations clearly confirm Marconi's observations that the radiation from a bent antenna is unsymmetrical, being greatest in a direction opposite to that towards which the free end of the antenna points. It was also found that by bending down the free end towards the earth, as in Fig. 17, the radiation became still more unsymmetrical, as shown by the polar curve in Fig. 17, in which the radii represent the strength of the currents in the receiving antenna corresponding to various relative positions of the horizontal or inclined part of the transmitting antenna. It will be seen from the polar curve that the tipping down of the horizontal part causes nearly the whole of the radiation to be sent out towards that side opposite to which the free end points.

Marconi directed his attention also to the location of the radiant

point, and discovered experimentally that the form of bent antenna which projects its radiation most intensely in a direction opposite to that in which the free end points receives or absorbs best radiation arriving on it from the same direction. Hence, he employed such a

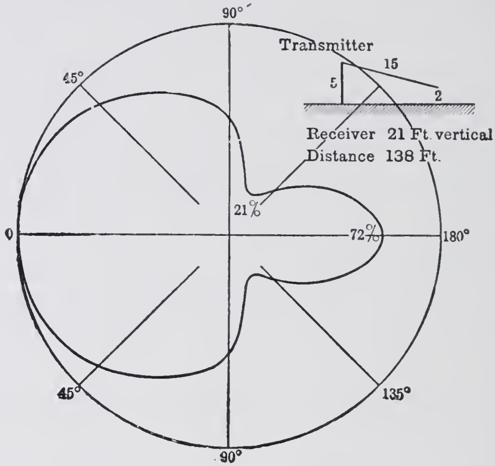


Fig. 17.—Polar Diagram, Radii of which denote Currents in the Receiving Antenna due to Radiation from a Bent Transmitter placed in Various Positions.

bent receiving antenna which could have its horizontal part swivelled round its vertical part to locate the direction of the sending antenna.

Marconi also invented a stellate receiving antenna consisting of a number of wires arranged in a radial manner from a centre to locate the direction of a sending station[11] (see Fig. 18). In this case a single oscillation detector or receiver has one terminal connected to an earth plate, and the other successively to the inner ends of the various radial antenna. Note is then taken of that position in which the signals are loudest, and the transmitter must then be in a direction opposite to that in which the free end of that particular radial receiving antenna, thus found to give the best signals, points.

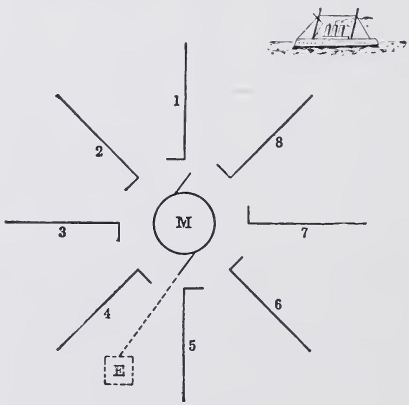


Fig. 18.

Marconi has given in his paper on directive antennæ (*loc. cit.*) a large number of observations, set out in the form of polar figure-of-eight curves, which delineate the intensity of the radiation in various azimuths from bent antennæ of various proportions by the length

[11] See G. Marconi's British Patent Specification No. 3127 of February 8, 1906.

of their *radii vectores*, and also the current induced in such a receiving antenna, and its power of locating the direction of the radiant point. We shall refer again to his work in the chapter on Radiotelegraphic Stations.

The observations of Marconi, and of the author also, confirm the truth of the deductions which can be made from the theory given in § 4. If we plot out the values of E given by equation (17), § 4, for the electric force of a bent antenna perpendicular to and in the equatorial plane for some fixed value of the quantity mr, but for varying values of the azimuthal angle ψ, it will be found that they plot out into a figure-of-eight curve, such as that in Fig. 15. Moreover, the theory above given shows that the non-symmetricality depends not on the distance r alone, but on mr, or on the ratio of distance to wave length, and upon the ratio of the lengths of the vertical and horizontal portions of the antenna.

This deduction also agrees with the observations of Mr. Marconi, who says [12] :—

> "I have observed that, in order that the effects should be well marked, it is necessary that the length of the horizontal conductors should be great in proportion to their height above the ground, and that the wave lengths employed should be considerable, a condition which makes it difficult to carry out such experiments within the walls of a laboratory.
>
> "I have found the results to be well marked for wave lengths of 150 metres and over, but have not been able to obtain as well-defined results when employing much shorter waves, the effects following some law which I have not yet had time to investigate."

Another entirely different method of giving direction to electric waves has been devised by F. Braun, which depends upon the interference of electric waves travelling in the same direction but different in phase.[13] In Braun's method, three simple vertical wire antennæ are set up in positions corresponding to the angular points of an equilateral triangle, and oscillations are created in these antennæ which differ from one another in phase. These oscillations with definite phase differences were produced by a method devised by N. Papalexi and L. Mandelstam.[14] By these arrangements it is possible to cause the waves emitted by the three antennæ to combine together and assist one another in certain directions, but to neutralize one another in certain other directions.

The experiments were carried out on a large open space near Strasburg. Wooden poles 20 metres high were planted at the corners of an equilateral triangle whose sides were 30 metres long. Antennæ wires each approximately 33 metres long terminated in wire netting stretched parallel to the ground and at a small distance above it. These constituted the balancing capacities. In the centre of the triangle an observation hut was constructed from which the wires ran out horizontally to the masts at a height of $2\frac{1}{2}$ metres above the ground. At a distance of 1300 metres a receiving station

[12] See *Roy. Proc. Soc.*, A, vol. 77, p. 415, 1906.

[13] See *The Electrician*, vol. 57, pp. 222, 244, May 25 and June 1, 1906. Prof. F. Braun, on Directed Wireless Telegraphy.

[14] See *Science Abstracts*, vol. 9, A., *abs.* 1277, 1906; or *Phys. Zeitschr.*, vol. 7, p. 303, 1906, "A Method of obtaining Oscillations in Different Phases."

was constructed and a receiving wire erected attached to a pole 20 metres high. In the circuit of this receiving wire was placed a hot wire oscillation detector, by means of which the current in the receiving wire could be measured.

In a number of the experiments the oscillations in two of the transmitting antennæ were of the same phase, but differed from these in the third antenna by a definite amount, say, by 100°. The amplitude of the oscillations in the two antennæ in the same phase was half that in the third antenna. Under these conditions, if observations are taken of the current in the receiving antenna at equal distances, but in different azimuths round the triple transmitter, it is found that in one direction the radiation is a maximum, and in the opposite direction it is nearly zero, varying in accordance with the radii of a polar curve, as shown in Fig. 19.

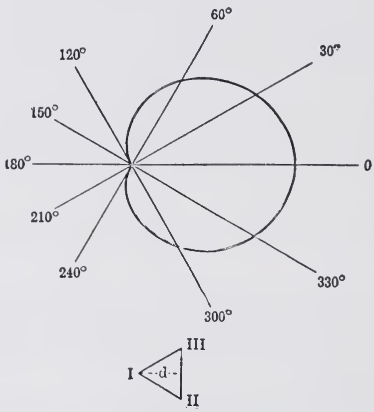


Fig. 19.

The method, although ingenious, has not the simplicity and practicality of the bent receiving and transmitting antennæ employed by Marconi.

Another very practical system of directive radiotelegraphy has been devised by E. Bellini and A Tosi.[15] They employ a nearly closed circuit transmitting antenna consisting of two aerial wires suspended from one mast, the upper ends being insulated and the lower ends brought into a signalling house, the wires being stretched out, as shown in Fig. 20, so as to give them the form of a triangle with its plane vertical. If oscillations are set up either by the direct coupled or inductive method, radiation takes place from this nearly closed antenna which is not symmetrical in a horizontal plane but is greatest and equal in the two directions in the plane of the antenna and zero at right angles to that plane; in other directions varying in accordance with the radii to a figure-of-eight polar curve, as shown in Fig. 21.

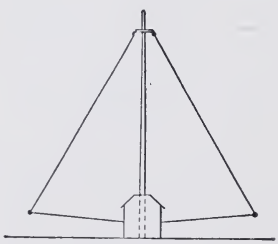


Fig. 20.—Bellini and Tosi Closed Circuit Antenna.

The nature of the electromagnetic field round such a closed oscillator may be illustrated experimentally by means of a pair of antennæ, each consisting of a long helix of fine wire, wound on an ebonite rod. If these spirals H_1, H_2 (see Fig. 22) are joined at the base through a pair of loops S, S, which are acted upon inductively

[15] See British Patent Specification, No. 21,299, of September 25, 1907. Also *The Electrician*, vol. 60, p. 748, 1908.

by the oscillations created in another pair of loops P, P, then we have oscillations in opposite phases created in the two helices. If the field around is explored by means of a vacuum tube filled with neon it will be found that in the plane of the two helices there is

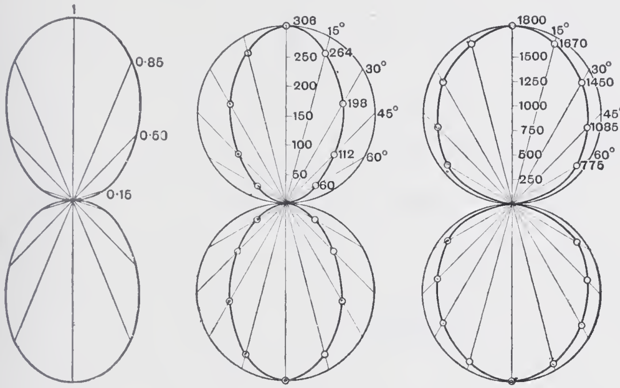


FIG. 21.

a stray field, but no field in a plane at right angles to the plane of the helices drawn through the median line. Hence such an antenna is directive in radiative quality.

The inventors employ a transmitting antenna and a receiving antenna of the same form. When used as a receiving antenna the oscillation detector, of whatever type it may be, is placed at the centre of the lower or horizontal side of the triangle. The intensity of the oscillations created in the nearly closed receiving circuit by the incident waves is then a maximum when the plane of the circuit coincides with the direction of propagation of the waves, and zero when it is at right angles to it. Such a circuit may be employed to discover the direction in which waves are travelling which fall upon it by swivelling the circuit into various positions round its vertical axis. MM. Bellini and Tosi, however, prefer to construct

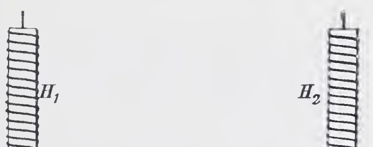


FIG. 22.

and erect two such circuits at right angles to one another at each station. Each of these circuits contains in its lower part a coil which can be acted upon inductively or can act inductively upon another circuit placed in an intermediate position, which last circuit either contains the oscillation producing arrangement, if it is a transmitter, or the oscillation detecting arrangement, if it is a receiver.

The arrangement is as shown in plan in Figs. 23 and 24. The pair of nearly closed antennæ forming the transmitting and receiving

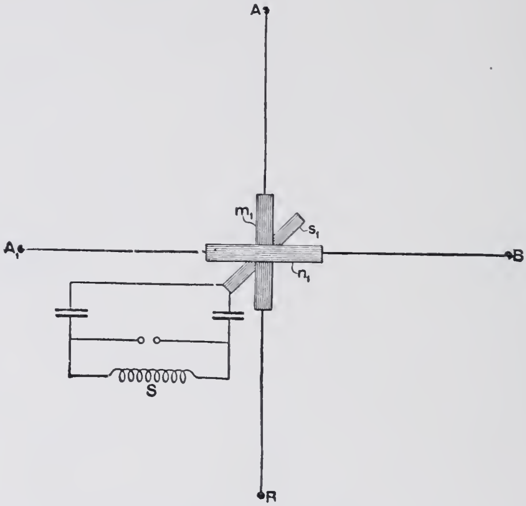
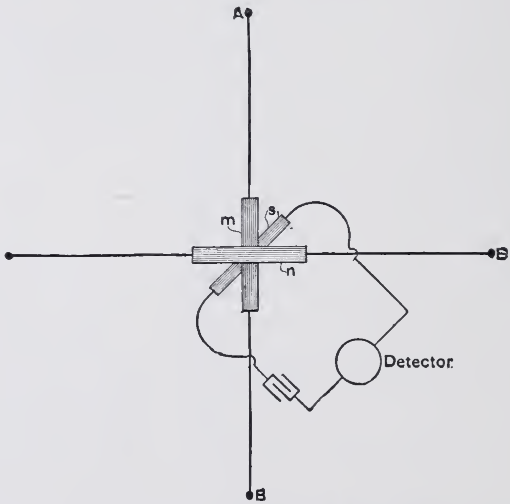


FIG. 23.—Diagram showing in plan Bellini and Tosi Crossed Closed Transmitting Antennæ.



[*Figs.* 20, 21, 23, 24, *are reproduced from "Electrical Engine ering" of November* 14, 1907, *by permission of the Proprietors.*]

FIG. 24.—Diagram showing in plan Bellini and Tosi Crossed Closed Receiving Antennæ.

arrangement respectively, are placed with their planes at right angles and the coils to be acted upon inductively, which are inserted in their lower portions respectively (shown in plan), also at right

angles. A third coil which forms, as it were, the primary or secondary circuit of an oscillation transformer, is placed close to and within the other two coils just mentioned, and in the transmitter this last-named coil is connected respectively with the condenser and a spark gap, and in the receiver with an oscillation detector. The coil in which the oscillations are either set up or are detected is capable of being swivelled round so as to be parallel with either of the fixed coils contained in the circuits of the pair or closed antennæ, or else occupy some intermediate position.

It is then found that the maximum intensity of the radiation from this pair of closed antennæ in quadrature or at right angles is a maximum in the direction of the plane of the primary inducing coil if we are concerned with the transmitter.

The elementary theory of the Bellini and Tosi compound directive antenna may be stated as follows:—

Consider a small square oscillator circuit placed with its plane vertical to the earth (see Fig. 25). Let the plane of the oscillator be taken as the plane of zy, and its centre as origin. Let the horizontal plane xy be called the equatorial plane. We have already obtained in § 3, in equations (9), (10) and (11), expressions for the electric and magnetic forces produced by such an oscillator. If in these equations we put $z = 0$, we obtain the electric and magnetic force components in the equatorial plane xy. For large distances from the oscillator these expressions are—

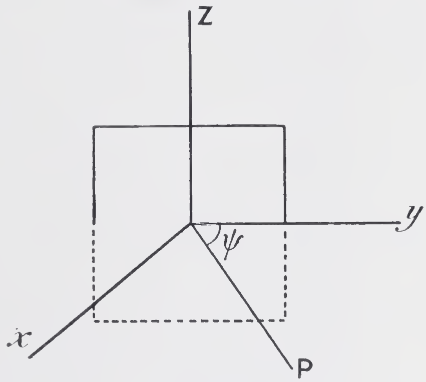


FIG. 25.

$$\left.\begin{aligned} Z &= \frac{\mathrm{AM}nm}{r}\cos\chi\cdot\frac{y}{r} \\ \alpha &= -\frac{\mathrm{M}m^2}{r}\cos\chi\cdot\frac{y^2}{r^2} \\ \beta &= \frac{\mathrm{M}m^2}{r}\cos\chi\cdot\frac{xy}{r^2} \end{aligned}\right\} \quad \ldots\ldots \quad (20)$$

where M is the magnetic moment of the closed circuit.

If we write $\cos\psi$ for $\frac{y}{r}$, $\sin\psi$ for $\frac{x}{r}$, C_1 for $\mathrm{AM}nm\cos\frac{\chi}{r}$, and C_2 for $\mathrm{M}m^2\cos\frac{\chi}{r}$, we can put the above equations in the form—

$$Z = C_1\cos\psi, \quad \alpha = -C_2\cos^2\psi, \quad \beta = C_2\sin\psi\cos\psi$$

The electric force Z is perpendicular to the equatorial plane, and the magnetic components α and β are in that plane. If we draw a radial line OP (see Fig. 25) in the equatorial plane xy making an

angle ψ with the y-axis, and if we represent the pair of crossed closed oscillators in plan as in Fig. 26, by the thick black lines AB, CD, which denote the traces on the xy plane of the pair of closed oscillators with their planes at right angles, it is easy to see that the resultant magnetic force in the plane xy and perpendicular to OP is $\beta \sin \psi - \alpha \cos \psi$ or $C_2 \sin^2 \psi \cos \psi + C_2 \cos^3 \psi = C_2 \cos \psi$. We find, then, that at P the electric force is $C_1 \cos \psi$ and magnetic force is $C_2 \cos \psi$, both being perpendicular to OP and at right angles to each other. Moreover, both these forces are proportional to the apparent area of the oscillatory circuit as seen from a position 90° removed in azimuth from OP.

Consider, then, two such closed oscillators, one in the plane of zy, and the other in the plane of zx, their centres coinciding with the origin and with each other. Let there be a third closed circuit, the trace of which on the xy plane is ab, placed with its plane vertical and centre coinciding with those of the other two, but its plane making any angle ϕ with the plane of zy. In this last circuit let oscillations be established. These will induce oscillations in the other two circuits, the intensities of the induced oscillations being respectively proportional to C $\cos \phi$ and C $\sin \phi$, where C is some constant. Hence the magnetic moments M_1 and M_2 of the fixed circuits will be proportional to C $\cos \phi$ and C $\sin \phi$ respectively. Therefore the electric and magnetic forces at any distant point P, perpendicular to OP, due to the currents induced in these two fixed circuits placed in the planes zy, zx respectively will be proportional to $CC_1 \cos \phi \cos \psi + CC_1 \sin \phi \sin \psi$ and to $CC_2 \cos \phi \cos \psi + CC_2 \sin \phi \sin \psi$. Accordingly, the resultant fields due to each will be proportional to $\cos(\psi - \phi)$. The resultant field is, therefore, a maximum for that value of ψ, viz. the azimuthal angle which makes $(\psi - \phi) = 0$. In other words, the radiation is most intense in the direction of the plane of the primary inducing circuit. If, therefore, this circuit can be swivelled round so as to vary the direction of its plane, we can project radiation of the maximum intensity in that direction and hence to that extent control the direction of the radiation. In practically carrying out this method the two secondary circuits connected to the two nearly closed antennæ are formed of highly insulated wire wound at right angles to each other on a cylindrical frame. In the interior of the cylinder is placed the primary coil capable of revolving round the axis of the cylinder. It is provided with an index needle moving over a graduated circle (see Fig. 27). This movable coil is connected to the condenser circuit in which oscillations are generated either by

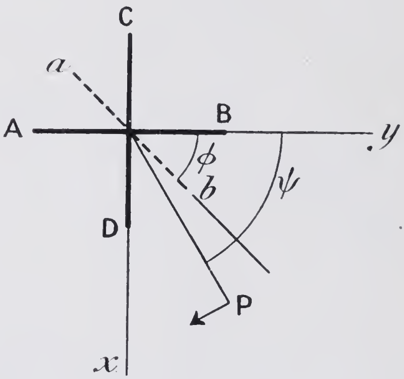


Fig. 26.

the spark or arc method. This coil can then be swivelled round, and, acting inductively in varying degree on the two fixed coils, as above explained, enables the maximum intensity of radiation from the duplex antenna to be created in the direction of the plane of the inducing or primary coil.

A similar arrangement is adapted for receiving and locating the direction of the transmitter. In this latter case the movable circuit is in connection with the receiving detector. Supposing the waves are incident on this compound receiving antennæ coming from a

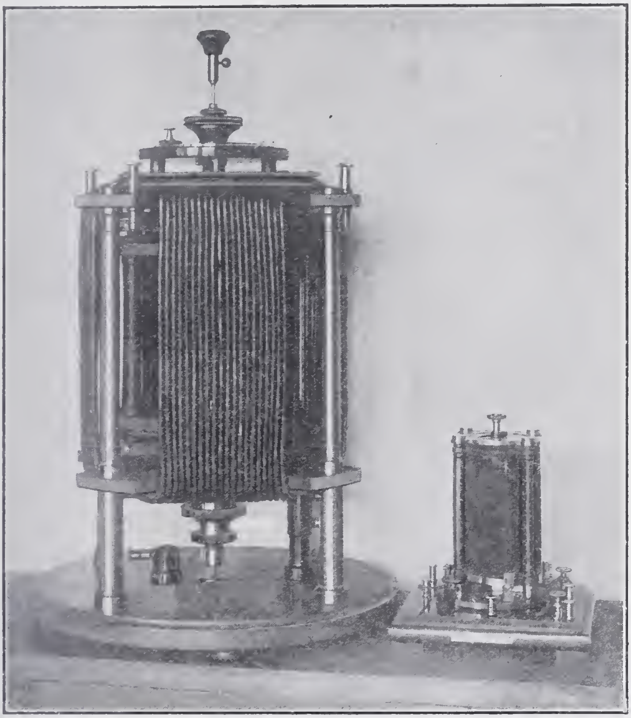
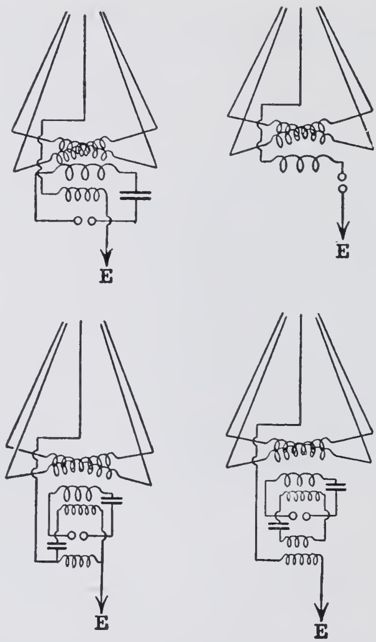


FIG. 27.—Bellini and Tosi Radiogoniometers. The Instrument on the left is the Transmitting and that on the right the Receiving Radiogoniometer.

certain direction. In order to determine that direction, all that is necessary is to swivel round the secondary coil in direct connection with the oscillation detector so as to place it parallel to one or other of the primary coils inserted in the closed circuit antennæ or in some intermediate position. Some position will then be found in which the indications of the oscillation detector are a maximum, and when that is the case, the waves must be falling on the compound antennæ in the direction of the plane of the secondary coil attached to the oscillation detector. In the same way, to send out radiation which is a maximum in any given direction, the coil in which the oscillations are being produced is swivelled round so as to be parallel

to one or other of the secondary coils inserted in the circuits of the two closed circuit antennæ, and the radiation will then be a maximum in the direction in which that coil points. This instrument, which enables the antennæ to remain fixed, but a certain coil coupled to the antennæ inductively to be rotated so as to act on or be acted on by either antenna more or less, is called by Bellini and Tosi a *radiogoniometer*.

Experiments with this system showed that good results could be obtained with an expenditure of less than 500 watts between Dieppe and Havre (55 miles overland) and Dieppe and Barfleur



[*Figs. 28 and 29 are reproduced from "Electrical Engineering," by permission of the Proprietors.*]

FIG. 28.—Bellini and Tosi Compound Antenna for Directive Radiotelegraphy.

(110 miles over sea). The angles between the stations, Dieppe-Havre-Barfleur is 23°, but the Dieppe-Barfleur transmission did not affect the Havre, nor did the Dieppe-Havre transmission affect Barfleur. The height of the antennæ was 48 metres, the wires being 60 metres long at the base and 60 long in the inclined side, forming an equilateral triangle, each side of which was 60 metres in length. It was also found that this closed circuit system was more proof against disturbances from atmospheric electricity than the system employing open circuit antennæ.

By employing a single vertical antenna coupled inductively to a condenser circuit, to which also a pair of nearly closed circuit antennæ are coupled (see Fig. 28), the same inventors have been able to confine the radiation entirely to one side of the compound antennæ as indicated by the cardioid curve in Fig. 29.

This complex form of antenna is particularly interesting, as it affords an insight into the possibility of constructing compound antennæ which shall project their maximum intensity of radiation in one or more required directions, just as a Fresnel lens can be constructed to project the light from a lighthouse lamp along one or more directions. The theory of the action of a complex antenna consisting of a plain vertical open antenna situated symmetrically, or at the centre of a pair of closed circuit antennæ at right angles, or in quadrature with each other, has been given by Messrs. Bellini and Tosi as follows [16] :—

We have seen that the polar diagram of the energy radiation along the equatorial plane of a closed oscillatory circuit is a figure-of-eight

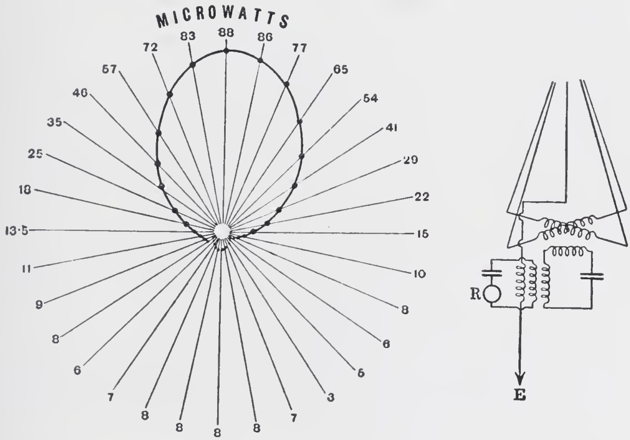


FIG. 29.

curve, or lemniscate, which may be represented by two circles touching each other (see Fig. 30, a_1, a_2).

If we associate with the closed circuit a vertical open circuit the radiation diagram of which is a circle, b, the polar curve of radiation from this compound antenna is obtained by adding the radii vectors of the curves a_1, a_2, and b, having regard to direction. We then obtain the resultant curve c, which is a heart-shaped curve, or cardioid, its radii vectors representing by their length the resultant field of the compound antenna in various directions.

Algebraically it can be represented as follows :—

The electromagnetic field produced by the closed circuit at any point of which the radius vector makes an angle α, with the direction of maximum radiation is C cos α where C is some constant, and if we denote the field due to the vertical antenna at the same distance by M_2 and denote by ϕ the phase difference between the fields of the

[16] See Messrs. Bellini and Tosi on "A Directive System of Wireless Telegraphy," *Phil. Mag.*, ser. 6, vol. 16, p. 638, 1908; also *Proc. Phys. Soc. Lond.*, vol. 21, p. 305, 1909.

open and closed antennæ, then the resultant field, I, will be expressed by the formula—

$$I = \sqrt{(M + C\cos\alpha\cos\phi)^2 + C^2\cos^2\alpha\sin^2\phi}$$
$$= \sqrt{M^2 + C^2\cos^2\alpha + 2MC\cos\alpha\cos\phi}$$

The minimum of I with reference to α is obtained when

$$\cos\alpha = -\frac{M}{C}\cos\phi$$

This value of $\cos\alpha$ is imaginary when $M\cos\phi > C$.

In the case when $M\cos\phi \leqq C$, we have $I_{min} = M\sin\phi$; when $M\cos\phi > C$ we have

$$I_{min} = \sqrt{M^2 + C^2\cos^2\alpha - 2MC\cos\alpha\cos\phi}$$

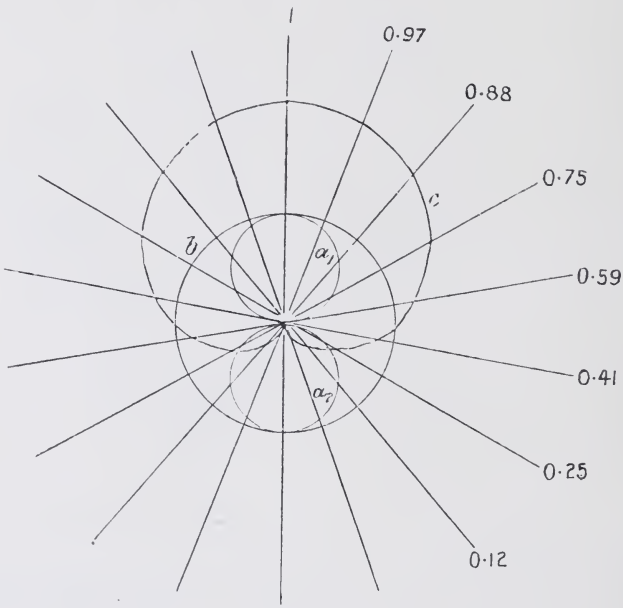


FIG. 30.

In the special case when $\phi = 0$ the equation of the resultant electromagnetic field transforms itself into

$$I = M + C\cos\alpha$$

which is the equation of a curve that can have three different forms according to the value of the ratio $\frac{M}{C}$. The curve represented by the condition $M = C$ is the cardioid above mentioned.

But since in wireless telegraphy the action depends chiefly upon the energy, it will be useful to consider this in preference to the intensity of the electromagnetic field.

In the general case the energy radiated in the different directions is expressed by the equation—

$$W = M^2 + C^2\cos^2\alpha + 2MC\cos\alpha\cos\phi$$

and in the case of the cardioid by the equation—

$$W = M^2 (1 + \cos \alpha)^2$$

The corresponding curve is given in Fig. 31.

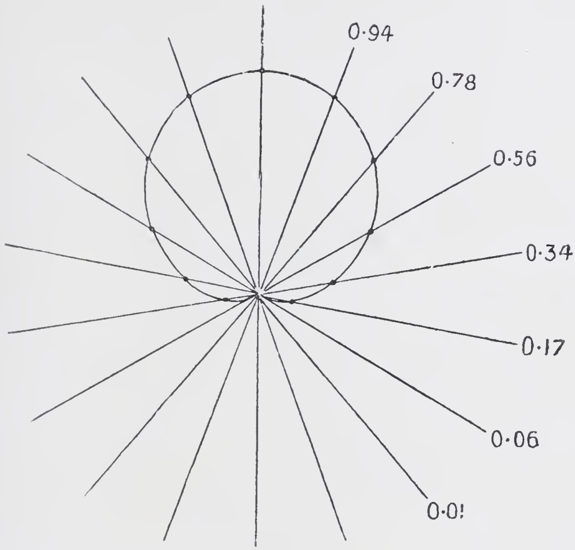


Fig. 31.

Fig. 32 represents the energy diagram in the case where

$$\frac{M}{C} = 0{\cdot}72 \text{ and } \phi = 53^\circ$$

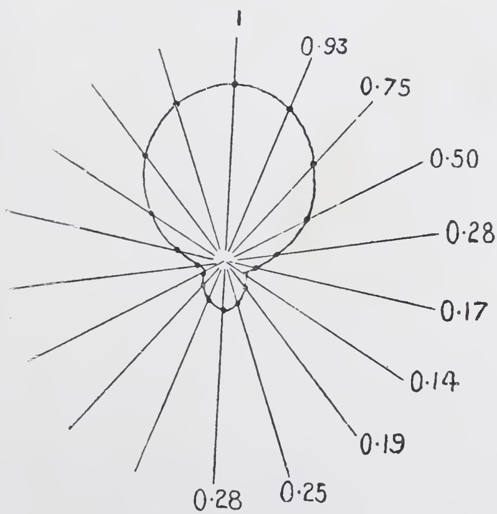


Fig. 32.

Fig. 33 shows the same diagram for the case where M = 2C and $\phi = 0$, and, finally, Fig. 34 the same diagram for M = C and $\phi = 90°$.

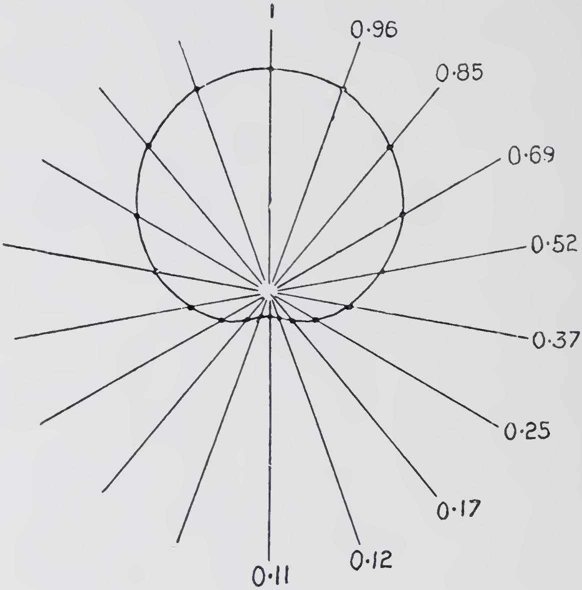


Fig. 33.

In consequence, one can conclude that the shape of the polar diagram, the radii of which represent the energy radiated in the different directions, depends upon the value of the phase-difference

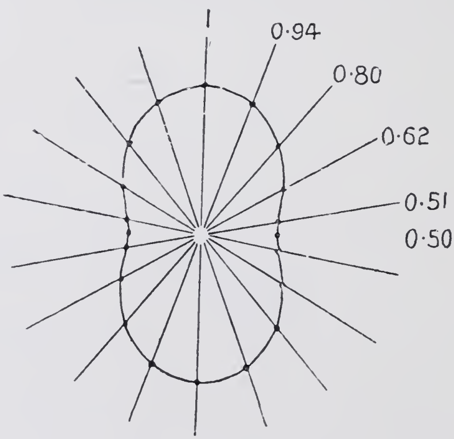


Fig. 34.

of the component electromagnetic fields, and that the superposition of a circular system on a directive system enables the emitted energy in any desired direction to be made a maximum.

The practical realization of the superposition of the two systems has been effected by employing as the directive system the double closed circuit antenna already described. It was evident *à priori* that, owing to the different conditions under which the radiation from the directive circuit takes place with reference to the radiation from the vertical antenna, a phase-difference between the emissions of the two systems should exist, for equality of phase in the excitations. Experiments have shown that this phase difference is 90°, or near to that value. The aerial of the unilateral system is formed by the aerial of the directive circuit, to which has been added a vertical antenna in a position symmetrical with reference to the first. To secure the simultaneous excitation of the closed oscillatory circuits, and of the vertical antenna, various arrangements have been employed, which are diagrammatically depicted in Fig. 28.

In the first of these arrangements the excitations of the two systems are in phase; in the other three cases they are in quadrature. The diagrams of the energy radiated in the different directions, as shown in Figs. 31 to 34, are selected from a large number of polar radiation curves experimentally obtained by MM. Bellini and Tosi, and figured in their paper (*loc. cit.*). For additional information the reader may be referred to the translation of a paper by MM. Bellini and Tosi which was published by Mr. L. H. Walter in *Electrical Engineering* (London) for November 14, 1907, vol. 2, and March 5, 1908, vol. 3. Also to their papers in the *Jahrbuch der Drahtlosen Telegraphie und Telephonie*, vol. 1, p. 598, 1908; vol. 2, p. 381, 1909; and vol. 2, p. 608, 1909. Also to a paper in the *Proceedings of the Associazione Electrotechnica Italiano*, 1909, entitled "Sistema di Telegrafia senza fili dirigible," and to a paper by Capt. M. Tosi, in the *Proceedings of the Société Internationale des Electriciens*, vol. viii., 1908, entitled "Télégraphie et Téléphonie sans fils dirigéables." Also to the British Patent Specification, No. 11,544 of 1909, by Marconi's Wireless Telegraph Company, Ltd., and H. Round.

6. The Measurement of the Capacity and Insulation of an Antenna.—An important quality of an open antenna is its capacity with reference to the earth, as it is upon this that the current into it partly depends. A single insulated wire or rod erected in air in a nearly vertical position has a certain capacity with respect to the earth, and we may consider that the wire forms the inner coating of a Leyden jar, of which the earth's surface is the outer coating and the space round the dielectric. We have shown (see Chap. II. § 7) that the capacity of such a circular-sectioned wire of length l and diameter d cms. is given by the formulæ—

$$\text{C (in electrostatic units)} = \frac{l}{2\log_\epsilon \frac{2l}{d}} \quad \ldots\ldots \quad (21)$$

$$\text{or C (in microfarads)} = \frac{l}{4{\cdot}6052 \log_{10}\frac{2l}{d} \times 9 \times 10^5}$$

$$\text{or C (in micro-microfarads)} = \frac{0{\cdot}241 l}{\log_{10}\frac{2l}{d}} \quad \ldots\ldots \quad (22)$$

We have given one instance to show that these expressions will in general assign a capacity rather smaller than that given by actual measurement, since the formula is based on the supposition that the earth is at a considerable distance from the wire. Nevertheless, if we desire to predetermine approximately the capacity of a single *very thin* vertical aerial wire having one end near the earth, we can do so by increasing the value given by the above formulæ by about 10 per cent.

Thus a wire 0·1 inch in diameter, 7/22 S.W.G. in size, and 200 feet long, upheld in a nearly vertical position with base near the earth, was found to have a capacity of 0·00038 mfd., whereas the above formula would predetermine it to be 0·00033 mfd.

This matter has been experimentally examined by A. E. Kennelly and S. E. Whiting (see *Electrical World*, New York, vol. 48, p. 1239, 1906; or *Science Abstracts*, vol. x. A., 1907, *abs.* 290).

If a metal rod and plate are immersed in a conducting fluid, then the electrical resistance between the plate and metal in various positions is inversely proportional to the electrostatic capacity between them in the same positions, if we suppose the conducting fluid replaced by a dielectric medium. Hence, if a copper wire and large copper plate are immersed in a solution of sulphate of copper, the measurement of the resistance between them in various positions leads to a knowledge of the capacity of that wire with respect to the plate when both are in air. According to the measurements of Kennelly and Whiting, the capacity of a metal cylinder 80 diameters long is about 8·9 per cent. greater when the lower end of the cylinder is near the ground than it is when the cylinder is far removed and in free space.

It has already been pointed out that if a number of insulated wires or strips are placed parallel and near to each other, the actual measured capacity falls short of the sum of the capacities of each wire taken alone and separate in space, by an amount which is greater as the wires are nearer together. This is shown by the figures in Table I., obtained in the Pender Laboratory, University College, London.

A number (1 to 11) of flat iron strips about 1 inch wide, 15 feet long, and 0·05 inch thick, were hung up in a large room, and the capacity measured with the strips at different distances apart. The results in arbitrary units were as follows:—

TABLE I.

Number of strips.	Distance apart in inches.				Sum of separate capacities.
	12 inches.	6 inches.	3 inches.	In contact.	
1	1·00	1·00	1·00	1·00	1·0
2	1·74	1·45	1·34	1·19	2·0
3	2·31	1·80	1·61	1·27	3·0
4	2·79	2·10	1·85	1·44	4·0
5	3·28	2·42	2·03	1·46	5·0
6	3·75	2·70	2·21	1·54	6·0
7	4·18	2·98	2·36	1·59	7·0
8	4·61	3·25	2·52	1·72	8·0
9	5·03	3·51	2·68	1·81	9·0
10	5·46	3·77	2·82	1·96	10·0
11	5·90	4·00	2·97	1·99	11·0

This result shows that if a large number of wires are arranged in parallel to form a cage or conical aerial, the capacity of the whole is not nearly equal to that of the sum of the separate wires when very far apart.

From other experiments the writer has found that four equal and parallel wires, placed at a distance of about one-fiftieth of their length apart, have only twice the capacity of one wire, and twenty-five wires only about five times the capacity of one wire.

Hence, in the case of multiple wire aerials, the only way to determine the capacity is to measure it by means of the methods described in Chap. II., with the rotating commutator. However complex in form, the aerial has a certain capacity with respect to the earth which is best expressed in micro-microfarads.

We give below, in Table II., the measured results obtained in certain definite cases, which will be a guide in estimating.

TABLE II.

CAPACITY OF AERIAL WIRES OR ANTENNÆ IN MICRO-MICROFARADS (MMFDS.).

1 mmfd. = 10^{-6} of a microfarad.

A vertical wire 0·1 inch diameter and 110 feet long, with bottom end 5 feet from the earth suspended in the open air . . .	= 205 mmfds.
A nearly vertical wire 0·1 inch diameter and 200 feet long, with end near the ground suspended in the open air	= 380 ,,
A single wire ship aerial, wire about 0·1 inch diameter and 150 feet long	= 300 ,,
A vertical wire 0·14 inch diameter and 12 feet long, hung up in a large room	= 32 ,,
A single wire of 0·1 inch diameter and 14 feet long, suspended vertically in a large room	= 40 ,,
Four vertical parallel wires 110 feet long and 0·1 inch diameter, spaced 6 feet apart at angles of a square	= 583 ,,
Twenty-five vertical wires 0·1 inch diameter 200 feet long, arranged fan-shape with top ends about 2 feet apart . . .	= 1640 ,,
One hundred and sixty wires, each 0·1 inch diameter and 100 feet long, arranged conically with bottom ends together 10 feet above ground and top ends 2 feet apart	= 2685 ,,
Four vertical wires 0·1 inch diameter, each 45 feet long, placed fan-shape in front of a building 6 feet apart, bottom ends 10 inches apart connected to copper bus bar	= 485 ,,

The inference to be drawn from the above figures is that, as regards mere capacity, a few wires spaced far apart are better than a great many close together. The capacity of an aerial may be increased, however, by adding metal cylinders or galvanized iron wire netting cylinders at the top to a considerable extent. Such *capacity areas*, as they are called, are electrically equivalent to an increase in length in the wire.

Otherwise a horizontal length of wire may be added in one or both directions at the top of a vertical wire, making what is called a T-shaped aerial wire.

It can be shown that the capacity of a horizontal wire of diameter d cms. and length l cms., placed at a height of h cms. above the ground, is given in electrostatic units by the formula—

$$C = \frac{l}{2 \log_\epsilon \frac{4h}{d}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

and in micro-microfarads (mmfds.)[17] by the expression—

$$C = \frac{0 \cdot 2415 l}{\log_{10} \frac{4h}{d}} = \frac{l}{4 \log_{10} \frac{4h}{d}} \text{(nearly)} \quad . \quad . \quad . \quad . \quad (24)$$

Hence, if we construct a T-shaped aerial or antenna, of which the vertical member is l_v cms. long, and the horizontal member l_h cms. long, and if the wire is d cms. in diameter, the horizontal part being h cms. above the ground, the capacity in micro-microfarads would be *approximately* given by the formula—

$$\text{C (in micro-microfarads)} = 0 \cdot 241 \left\{ \frac{l_v}{\log_{10} \frac{2l_v}{d}} + \frac{l_h}{\log_{10} \frac{4h}{d}} \right\}$$

or if l_v is nearly the same as h, it would be nearly given in micro-microfarads by the expression—

$$C = \frac{l_v}{4 \log_{10} \frac{2l_v}{d}} + \frac{l_h}{4 \log_{10} \frac{4l_v}{d}} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

As a matter of fact, it would probably be about 10 per cent. greater than the value so predetermined on account of the proximity of the lower end of the vertical wire to the earth. It is not strictly correct, however, to assume that the total capacity of the horizontal and vertical wires is the sum of the capacities of each separately, since the formulæ for the individual capacities have been obtained on the assumption that each wire was free in space. It is not generally true that the capacity of a body made up of parts is equal to the sum of the capacities of each part separately, because bringing them in contact creates a change in the distribution of electricity in each part. Nevertheless, for approximate predeterminations the above formula may be used. As an instance of the degree of divergence between theory and practice, we may give the following values. A horizontal wire 500 feet long and 0·164 cm. in diameter was stretched 6 feet above the ground. The capacity calculated by the formula given above was predetermined to be 1000 mmfds. The actual measured value was 1081 mmfds. The difference was therefore 8 per cent. If this wire had been at a higher elevation the difference would have been much less. Since long horizontal spans of wire are much cheaper to erect than long vertical ones, we can obtain an antenna of considerable capacity by making use of T-shaped wires. The logical extension of this idea is the umbrella aerial or antenna, mentioned in the previous section, consisting of a number of wires starting from a point just above the ground, rising cone-fashion to a certain height, and then passing horizontally outwards in radial directions.

Although the use of horizontal metal plates placed at a height above the ground has been suggested, yet an aerial made in this manner is unpractical, because the surface exposed to wind would cause it to be soon wrecked.

[17] See J. A. Fleming and W. C. Clinton, "On the Measurement of Small Capacities and Inductances," *Phil. Mag.*, May, 1903, ser. 6, vol. v. p. 505.

It is always desirable to measure the capacity of an aerial experimentally, and thus accumulate experience as to the capacity of given types of antenna. No method is so convenient as the rapid charge and discharge method involving the use of the rotating commutator described in Chap. II.

The antenna A is attached to the middle brush, and one terminal of a well-insulated battery, B, and of a movable coil galvanometer, G, to each of the outside brushes respectively of a rotating Fleming and Clinton commutator (see Fig. 35). The other terminals of battery and galvanometer must be put to a good earth, E. On setting the commutator in rotation, the antenna is alternately charged by the battery and discharged through the galvanometer. The antenna must, of course, be well insulated at the top. The process of calibration of the galvanometer and calculation of the capacity have already been described (see Chap. II. § 7).

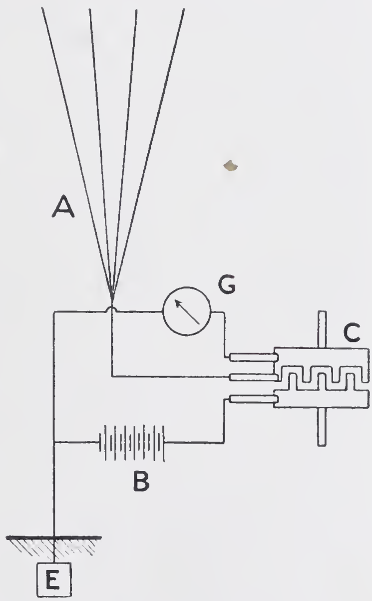


FIG. 35.—Mode of determining the Electrical Capacity of an Antenna, A, by means of a Rotating Commutator, C, Battery, B, and Galvanometer, G.

Previously to taking a measurement of an antenna it is always necessary to determine its insulation. This can best be done by ascertaining what current as measured by a sensitive galvanometer can be detected when this galvanometer is inserted between the antenna and a battery having one terminal to earth and the other to the second terminal of the galvanometer.

For this purpose a battery of small secondary cells, say 50 or 100 cells, made up in test tubes, is very useful. The battery must in general have an electromotive force of 50 to 200 volts. A convenient substitute for a battery is the small self-exciting dynamo or magneto machine contained in an Evershed and Vignoles "Megger" for measuring insulation resistances. This little dynamo has an electromotive force of 500 volts or so. The first step is to calibrate a sensitive mirror galvanometer so as to know the current in microamperes corresponding to any observed deflection or scale displacement of the spot of light. This being done, one terminal of the galvanometer is connected to the insulated antenna, which must be previously disconnected from the earth plate, and the other terminal of the galvanometer is joined to the insulated terminal of the battery or dynamo, the second terminal of the latter being connected to the earth plate.

We then observe the deflection of the galvanometer, and determine the current flowing into the antenna in microamperes. If we

then determine the electromotive force of the battery or dynamo in volts, the quotient of this voltage by the current in microamperes gives us the insulation resistance of the antenna in megohms. It is well to try the experiment first with a low voltage battery or single cell, and a coarse galvanometer or simple detector, lest there should be an accidental contact of the antenna with some non-insulated body. By this means the sensitive galvanometer will be preserved from destruction. As might be expected, the insulation of an ordinary antenna varies very much with the weather, being extremely high (several hundred megohms) in dry frosty weather and very low (perhaps a few hundred thousand ohms) in wet weather. The capacity measurement should always be made when the insulation is very high, as otherwise the charge put into the antenna by the battery partly leaks out before it can be discharged through the galvanometer by the rotatory commutator. For this reason in working the arrangement shown in Fig. 35, for measuring the antenna capacity by the commutator, it is always well to make two experiments, one with the galvanometer inserted in the charging circuit, or in series with the battery, and one with it in the discharge circuit or in parallel with the battery. The equality of the capacity measurements in the two cases is a proof of the good insulation of the antenna. If the insulation of the antenna is very good, then its capacity may be determined by charging it from a battery, say at 100 volts, and discharging this charge into a larger condenser, say, of $\frac{1}{3}$ microfarad size. If this process is repeated fifty to a hundred times, we accumulate a large charge in the large condenser, and this can be measured in the usual way by the "throw" given on a ballistic galvanometer by comparing the "throw" given when the accumulated charge in the condenser is due to, say, 100 discharges into it of the antenna charged at 100 volts with the "throw" given by the discharge of the same condenser charged at 2 volts.

At all radiotelegraphic stations regular measurements should be made of the insulation and capacity of the antenna, the former being stated in megohms and the latter in microfarads or micro-microfarads, or in electrostatic units of which 9×10^5 equal 1 microfarad.

7. The Oscillation Constant of an Antenna.—Another important quantity connected with an antenna is its *oscillation constant* which determines the wave length of the radiation emitted by it. Every antenna has its own natural period of electrical vibration, depending upon its capacity and inductance. We may compare it to a straight elastic strip of steel, gripped at one end in a vice. If we bend the strip and release it, it vibrates isochronously with a time period depending upon its flexural elasticity and its mass.

Consider the case of a fan-shaped antenna wire having a pair of spark balls near the base (see Fig. 36). Let the balls be connected with the secondary circuit of an induction coil, and electric oscillations set up in the wire. These are executed with a certain definite time period, depending upon the capacity and inductance of the wire. In the actual wire these two qualities are, so to speak, mixed up together, or there is so-called distributed capacity and inductance. We can, however, imagine an antenna in which the capacity is all collected at the top, and the inductance alone left in the wire. If the inductance

of the wire without capacity be denoted by L, and the capacity at the top is denoted by C, then it is evidently always possible to so adjust the magnitude of C and L that the hypothetical simple antenna has the same electrical time period of oscillation as the real complex antenna. In this case the imaginary capacity concentrated at the top is called the *equivalent capacity*, and the inductance of the vertical wire without capacity is called the *equivalent inductance*. If the equivalent capacity C is measured in microfarads, and the equivalent inductance L in centimetres, then the quantity $\sqrt{CL}$ is called the *oscillation constant* (O) of the hypothetical antenna.

The time period T of this last antenna is connected with its oscillation constant by the relation $T = \frac{O}{5{\cdot}033 \times 10^6}$.

The real antenna, which has the same time period, T, will also have the same oscillation constant. We can, therefore, define the oscillation constant of an antenna to be numerically equal to the product of its natural time period, T, and the constant $5{\cdot}033 \times 10^6$.

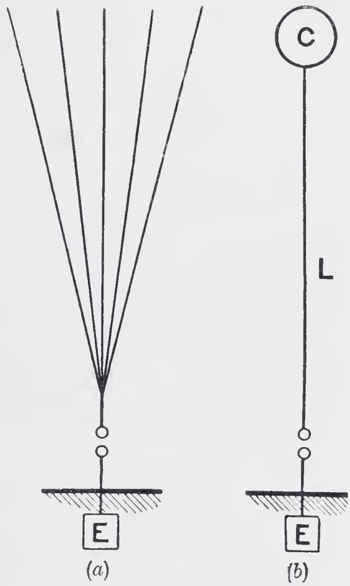


FIG. 36.—(*a*) Real Fan-shaped Antenna with Distributed Capacity, and (*b*) Ideal Antenna with Capacity localized at the Summit.

The mathematical predetermination of the oscillation constant of an antenna, in any but the simplest cases, presents great difficulties. It can, however, be obtained for a simple rod antenna as follows:—

Let l be the length in centimetres of the antenna supposed to be a circular-sectioned wire of diameter d, and let λ be the length in centimetres of wave radiated from it when it is giving its fundamental electrical oscillation. Then, since the velocity of radiation is 3×10^{10} cms. per second, if T is the natural time period of oscillation, we must have—

$$T = \frac{\lambda}{3 \times 10^{10}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Hence the oscillation constant O is given by $O = \frac{5\lambda}{3 \times 10^4}$.

The relation between l and λ for a single thin wire antenna is expressed by $\lambda = 4l$, but for a fan or multiple antenna, such as that shown in Fig. 36, it is more nearly $\lambda = 5l$.[18]

On the first supposition we have $O = \frac{l}{1500}$, and on the second $O = \frac{l}{1200}$.

[18] See Mr. H. M. Macdonald, Adam's Prize Essay, "Electric Waves," p. 111.

We can, to some extent, decide between these formulæ as follows:—

We have shown that the actual capacity in microfarads of the rod oscillator is—

$$C = \frac{l}{2 \log_\epsilon \frac{4l}{d} \times 9 \times 10^5} \text{ mfds.} \quad . \quad . \quad . \quad . \quad (27)$$

and its inductance—

$$L = 2l\left\{\log_\epsilon \frac{4l}{d} - 1\right\} \text{ cms.} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

Also, we have proved (see Chap. III. § 8) that the equivalent capacity of such a rod oscillator is $\frac{2}{\pi}$ of its real capacity.

In most actual wire antenna wires used the ratio $\frac{4l}{d}$ is near to 10^5, and $\log_\epsilon \frac{4l}{d}$ is, therefore, nearly 11·5. The actual inductance of the wires is then about 10 per cent. less than the value of $2l\left(\log_\epsilon \frac{4l}{d}\right)$, or L is equal, say, to $\frac{9}{10} \cdot 2l\left(\log_\epsilon \frac{4l}{d}\right)$ cms.

We can, therefore, say that the oscillation constant O of the thin vertical rod oscillator of length l is given by the expression—

$$O = \sqrt{\frac{2}{\pi} . C . L} = \sqrt{\frac{2}{\pi} \cdot \frac{9}{10} \cdot \frac{l^2}{9 \times 10^5}} \text{ nearly} \quad . \quad (29)$$

$$\text{or} \quad O = \frac{8l}{10^4} = \frac{l}{1250} \text{ nearly}$$

This value of O agrees more closely with the deduction from Macdonald's theory on which $\lambda = 5l$, and exactly with the relation $\lambda = 4{\cdot}8l$.[19]

Thus, suppose a simple aerial wire or antenna to have a height of 50 metres, or 5000 cms. Then its oscillation constant $O = \frac{5000}{1250} = 4$, and its time period $T = \frac{4}{5 \times 10^6}$ second.

For multiple antennæ or antennæ with capacity plates at the top, we cannot predetermine the oscillation constant, but it can be found experimentally with great ease by means of the author's cymometer (see Chap. VI. § 15).

Suppose any aerial or antenna, A, to be set up, and that it is desired to ascertain its natural time period or to adjust it to have any required time period. We provide the aerial with a pair of spark

[19] J. A. Pollock (*Journal of Roy. Soc. of New South Wales*, 1903, vol. 37, p. 198) found that for a linear oscillator of Hertzian type the ratio $\frac{\lambda}{l}$ was between 2·3 and 2·45. Hence for an earthed rod antenna it should be between 4·6 and 4·9; and this agrees with the above deduction and closely with Macdonald's theory.

balls, S, at the base inserted between the aerial and the earth plate, and place the Fleming cymometer, C*y*, with its copper bar parallel to and near the base of the aerial (see Fig. 37). We connect the spark balls to an induction coil, I, and set up oscillations in the aerial. The handle of the cymometer is then moved until the Neon vacuum tube of the cymometer glows most brightly, and the cymometer will then indicate the fundamental oscillation constant of the aerial by its scale reading, since when the cymometer is in tune with the aerial their oscillation constants must agree. In making this measurement the cymometer should be kept as far away from the aerial as possible, so as to avoid increasing the capacity of the aerial. We can then insert inductance in the earth wire of the aerial, or alter its capacity until we give it any required oscillation constant and natural time period.

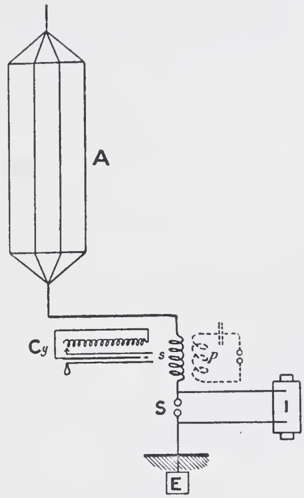


Fig. 37.—Mode of determining the Oscillation Constant of an Antenna by the Author's Cymometer. A, antenna under test; C*y*, cymometer; S, spark ball; I, induction coil; *ps*, oscillation transformer with primary circuits, *p*, out of operation; E, earth plate.

Thus, for instance, we may vary an inductance inserted in series with an aerial until we give it an oscillation constant of 5 or 10, corresponding to a natural time period of one-millionth of a second or one half-millionth of a second.

The measurement of the oscillation constant of the aerial gives us at once the length of wave radiated from it when used as a simple plain aerial in the original Marconi manner. For the velocity of electromagnetic radiation being 3×10^{10} cms. per second, or 10^9 feet per second nearly, it follows that the length of wave radiated is nearly 200 times the oscillation constant, when wave lengths are reckoned in feet, and 60 times when wave lengths are reckoned in metres. More exactly, the rules are—

$$\text{Wave length (in feet)} = 195{\cdot}56 \times \text{oscillation constant}$$
$$\text{Wave length (in metres)} = 59{\cdot}6 \times \text{oscillation constant}$$

the oscillation constant being the square root of the product of the capacity in microfarads and the inductance in centimetres.

Thus, for instance, an aerial set up at University College, London, had the form and dimensions shown in Fig. 38. The dimensions are given in feet and inches. It was arranged as a simple aerial 73 feet long. By means of the author's cymometer placed near to the lower horizontal bend, the oscillation constant was determined, and found to be 1·85. Hence the length of the fundamental wave radiated is 370 feet, and this is very nearly five times the total length of the aerial, since $5 \times 73 = 365$.

This measurement of the ratio of wave length to antenna length

agrees with Professor H. M. Macdonald's theory, and with the confirmation of it just given.

The above-described aerial wire then had an inductance coil of wire 60 feet in length inserted between the aerial and spark balls, this coil being the secondary circuit of an oscillation transformer (see Fig. 39). The total length of the open oscillating circuit was now 73 + 60 feet, or 133 feet. The oscillation constant was then found to be 4·85, and hence the fundamental radiated wave length was

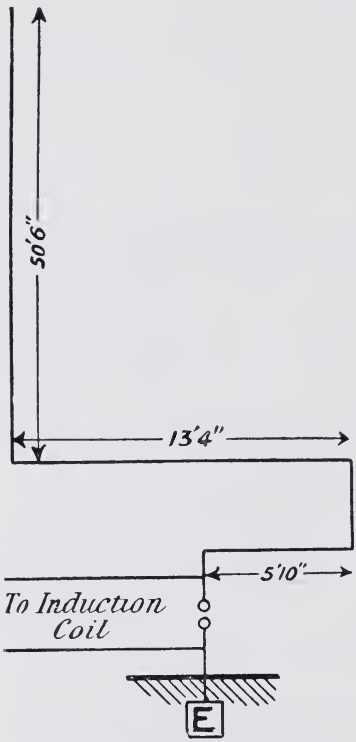


Fig. 38.—Dimensions of Antenna at University College, London, used for a Special Experiment as a Plain Aerial.

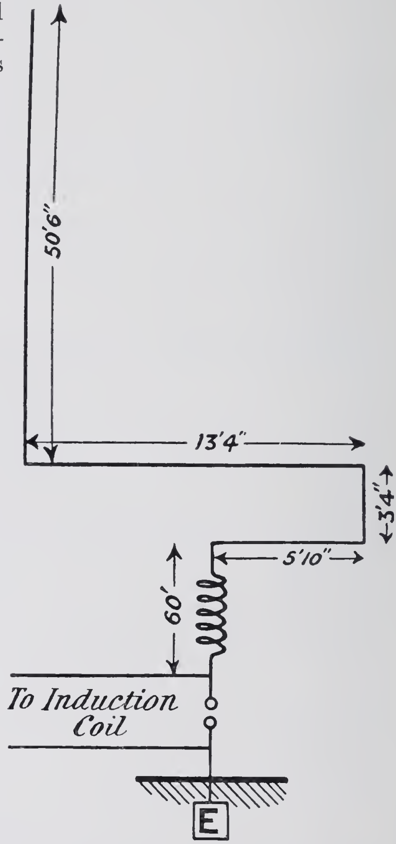


Fig. 39.—The same Antenna as in Fig. 38, but with an Inductance Coil inserted in Series with it above the Spark Balls.

now 970 feet. This is nearly equal to five times (73 + 2 × 60), thus showing that the 60 feet of wire wound on a frame forming the secondary circuit of the oscillation transformer was equivalent to much more than 60 feet of additional length to the aerial, owing to its greater inductance per unit of length. Hence a great error may be committed in estimating the radiated wave length even of a single wire aerial, if it is assumed (as some writers have done) that the wave length of the radiated wave is four times the total length of wire

composing the aerial, including that of any coiled wire forming an inductance in series with it.[20]

In a third case, a fan-shaped aerial of four wires, each 50 feet in length (see Fig. 40), and having the secondary circuit of an oscillation transformer in series with them, was tested in the same way. In this case the oscillation constant was found to be 6·9, and the radiated fundamental wave length 1380 feet. The above examples show how much the form, capacity, and inductance of the aerial affect the wave length of the radiated wave. Generally speaking, great errors have been made in guessing or assuming the radiated wave lengths of antenna in the absence of careful measurements with the cymometer.

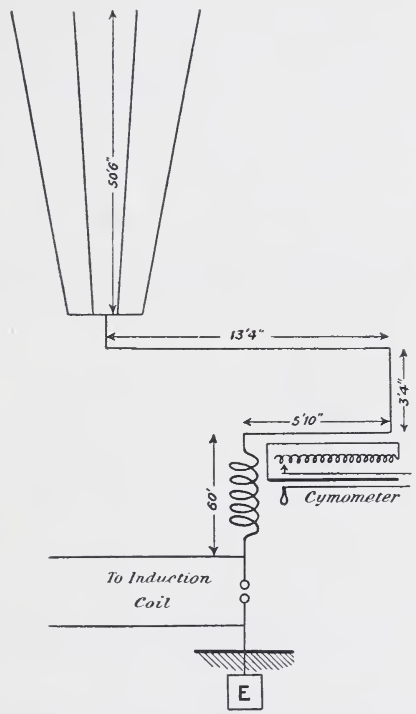


Fig. 40.—Determination of the Oscillation Constant of a Fan-shaped Antenna by the Cynometer.

8. The Nature of the Oscillations set up in Antennæ of Various Types.—We have in the next place to consider the nature of the oscillations produced in various types of antennæ, and the distribution of potential and current along it. When oscillations are taking place in the aerial, whether created by direct charge, as in the original Marconi method, or by coupling it to another closed oscillating circuit directly or inductively, two conditions must always hold good.

(i.) There must be a current node at the upper or insulated end, and a potential antinode or loop at the same place.

(ii.) At the earth plate end there must be a node of potential and an antinode or loop of current.

On the wire there will be produced, provided it has a suitable length, stationary waves of potential and current.

We have already given (see Chap. IV. §§ 1 and 2) the theory of the production of such stationary waves on wires. A general confirmation of theory has been obtained from experiments made with wire antennæ by Drude, Braun, Slaby, Chant, and Ives.

1. *The Oscillations in a Simple Antenna.*—Consider first the case of the original plain wire Marconi aerial. Theory shows that when oscillations are excited in it by disruptive discharge, the fundamental

[20] See Messrs. W. Duddell and J. E. Taylor, "Wireless Telegraph Measurements," *Journal Inst. Elec. Eng. Lond.*, 1905, vol. 35, p. 341.

oscillation is such that the potential oscillation has no amplitude at the earthed end, and a maximum at the insulated or top end, and that odd harmonic oscillations can exist, viz. the 3rd, 5th, 7th, etc., in which there are 1, 2, 3, etc., nodes of potential in addition to the node at the base, forming $1\frac{1}{2}$, $2\frac{1}{2}$, $3\frac{1}{2}$, etc., semi-waves of potential distribution on the wire, as indicated by the dotted lines in Fig. 19 of Chap. IV. In these diagrams the black lines indicate the antenna, and the distance of the dotted line from it the potential amplitude at that point. In the same manner, there will be loops and nodes of current with the condition that the free end is a node and the earthed end a loop of current.

Experience shows that it is not easy to excite the higher harmonics in a plain antenna. The most usual mode of oscillation is the fundamental. The explanation of this is probably to be found in the fact that owing to their greater frequency the higher harmonics are better radiated than the fundamental vibration. Hence the antenna tends to get rid of its harmonic oscillations, and to keep going its fundamental

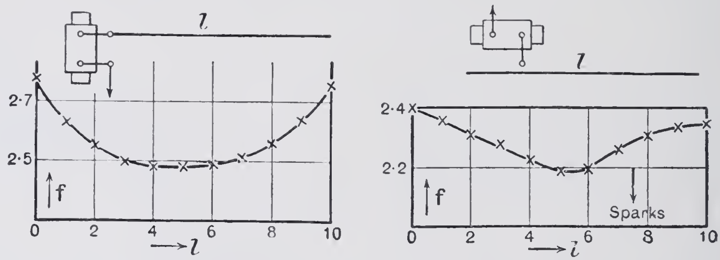


FIG. 41.—Diagrams illustrating the Results of Slaby's Experiments on the Distribution of Potential along a Linear Oscillator. The ordinates of the curved line denote spark potentials at the corresponding points in the wire.

oscillation. Thus F. Braun explored the potential distribution in a horizontal free-ending wire attached at one end to one secondary spark ball of an induction coil, the other ball being earthed or attached to an equal wire or capacity.[21] Braun hung on to the wire vacuum tubes at various places, each vacuum tube having a short tail of wire attached to its lower end, and he found no evidences of potential nodes, but a general increase in potential along the wire from the spark ball to the free end. Slaby made a more careful exploration, measuring the potential at each point in the antenna by means of a spark micrometer consisting of a blunt metal point opposed to a flat surface of carbon, the distance being capable of adjustment by a fine screw.[22] He earthed one of the secondary spark balls of an induction coil, and attached to the other a horizontal wire antenna 10 metres long and 1 mm. in diameter. He explored the distribution of potential along this wire. He found a distribution of potential as represented by the ordinates of the dotted line in Fig. 41, showing the existence of a stationary wave of potential in the wire with a minimum in the middle

[21] F. Braun, *Phys. Zeitschrift*, 1900, vol. iii. p. 143.
[22] See A. Slaby, *Elektrotechnische Zeitschrift*, 1902, p. 168; or *The Electrician*, 1902, vol. 49, p. 6.

of its length. Higher harmonics were absent. If two equal insulated antennæ were attached to the two spark balls, then a regular distribution of increasing potential was found in each wire, as shown by the ordinates of the dotted line, where the abscissæ represent distance from the spark balls of the coil, and the ordinates the micrometer spark length or potential amplitude at that point in the antenna.

C. A. Chant has also made similar measurements, using a form of Rutherford magnetic detector attached to the horizontal antenna by which to measure the potential or current at that point in the wire.[23] He employed as antenna a bare copper wire 0·7 mm. in diameter, stretched horizontally, and attached one end to one secondary spark ball of an induction coil, the other ball being either (1) earthed, (2) attached to an equal antenna, or (3) left insulated. He varied the length of the antenna from 500 to 2000 cms., and delineated a series of curves, the ordinates of which represent the potential amplitude in the antenna and the abscissæ distances from the free end. In the case when one spark ball was earthed these curves show a general increase in potential along the wire from the spark balls to the free end, but the curve is somewhat irregular; and in the case of the antenna 1000 cms. long there is a decided minimum or node of potential at 150 cms. from the free end (see Fig. 42, curves A).

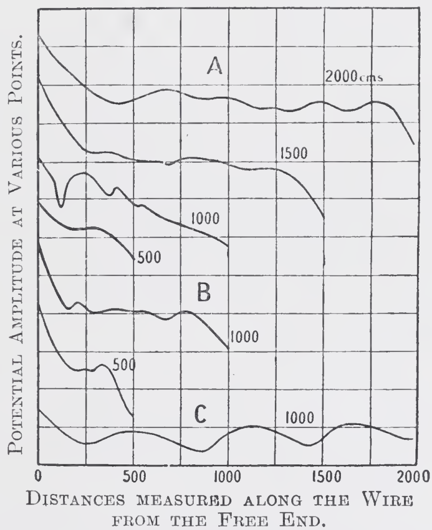


FIG. 42.—Curves obtained by Chant, representing the Potential Distribution in a Linear Oscillator directly charged. Curves A, one spark ball earthed; Curves B, equal wires attached to spark balls; Curves C, one spark ball insulated.

In the case when one spark ball of the coil was not earthed (curves C) there was no general rise of potential along the antenna attached to the other ball, but a series of nodes and loops of potential, the nodes appearing at distances 130, 425, 715, 1000 cms. from the end of the antenna 1000 cms. long. These clearly correspond to a stationary harmonic oscillation of $3\frac{1}{2}$ semi-waves of potential, each having a wave length of 580 cms. For $3 \times 290 + 130 = 1000$, and as we always find that the final semi-loop is less than one-quarter of a wave length, in fact, nearly one-fifth of a wave length, this agrees with the above observations.

Hence we can say that experiment confirms the theory that the excitation of electric oscillations in a simple vertical antenna, earthed

[23] See C. A. Chant, "On the Variation of Potential along Transmitting Antenna in Wireless Telegraphy," *The American Journal of Science*, January, 1904, vol. 17.

at its lower end through a spark gap, results generally in the production of the fundamental oscillation of the antenna with a potential amplitude, increasing all the way up the wire from the bottom or earthed end up to the top or free end. Also that the length of the wire comprises something rather less than one-quarter of a wave of potential.

There seems to be some difference of opinion as to the ratio between the wave length λ and actual length l of a simple linear Hertzian oscillator. If a pair of rods, very thin compared with their length, are placed in one line, the total length of the oscillator being l, then the wave length of the waves emitted when they are used as a Hertzian oscillator is, according to the theory of M. Abraham (*Wied. Ann.*, 1898, vol. 66, p. 435), equal to $2l$, and Lord Rayleigh agrees (see *Phil. Mag.*, 1904, vol. 8, p. 105). According to the theory of Prof. Macdonald, the ratio is $2{\cdot}53l$.

The experimentally determined ratios lie between these two extremes. Thus P. Drude, for a rod oscillator of 1 mm. diameter and 4 metres long, found $\frac{\lambda}{l} = 2{\cdot}1$ (see *Ann. der Physik*, 1903, vol. 11, p. 965), and this was confirmed by F. Conrat. A result in close agreement for thin-wire oscillators from 8 to 30 metres long has been obtained by Prof. G. W. Pierce (see *Proc. Amer. Acad. of Arts*, vol. 45, March, 1910), who found a mean value of 2·094. On the other hand, A. D. Cole, for an oscillator 3 mm. in diameter and 80 mm. long, found $\frac{\lambda}{l} = 2{\cdot}52$, which is in accordance with Macdonald's theory.

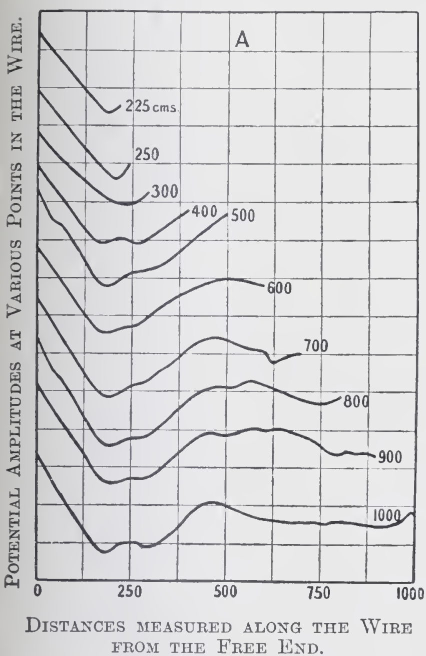
For a thin single-wire Marconi antenna of height h the ratio $\frac{\lambda}{h}$ may approach 4, but is generally a little larger, and for a branched antenna or thick rod experiment generally finds a ratio near to or a little below 5.

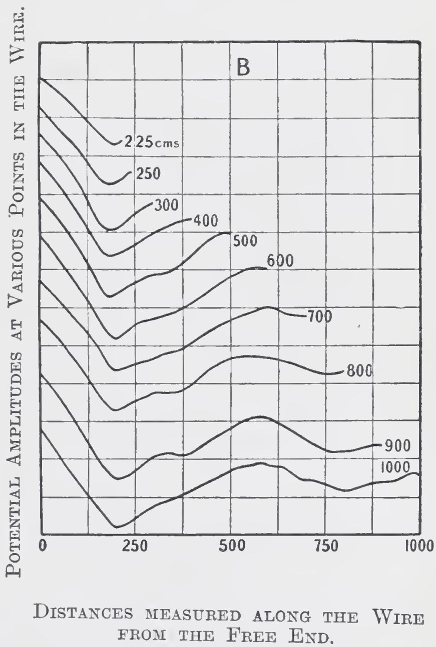
2. *The Oscillations in an Inductively Coupled Antenna.*—Mr. Chant also studied the distribution of potential in an antenna in which the oscillations were excited inductively or by contact with a closed oscillating circuit. He varied the length of the antenna (from 225 to 1000 cms.) attached to one terminal of the secondary circuit of the oscillation transformer, the other terminal of this transformer being attached (1) to earth, (2) to an antenna of equal length, (3) to a large capacity, and (4) insulated (see Figs. 43 and 44).

In each case he explored the potential distribution, and found always a minimum of potential at some distance between 150 and 200 cms. from the free end of the antenna. In the case of antennæ longer than 500 cms., there seemed to be a secondary maximum of potential between 450 and 600 cms. from the free end, and a secondary minimum at about 750 to 800 cms. from the free end (see Fig. 44).

In the majority of instances there was no agreement between the natural time period of oscillation of the condenser circuit and that of the inductively or directly connected antenna. Hence the oscillation created on the latter was a forced oscillation, and the distance from the free end of the wire to the first minimum of potential may be taken as equal to rather less than one-quarter of the wave length due to the closed circuit oscillator. Chant's conclusions are that by the

inductive method of connection between non-syntonized circuits, we excite in the antenna chiefly a forced oscillation due to the condenser circuit, and that the change in the length of the antenna makes but little difference in the position of the first node, provided the antenna is long enough to contain at least one-quarter of a stationary oscillation due to the condenser circuit. On the other hand, in the case of the simple Marconi aerial and the antenna direct-coupled to a condenser circuit, the principal oscillation is the fundamental vibration of the antenna itself; the most effective arrangement in





Chant's Curves representing the Potential Distribution in an Inductively Coupled Antenna.

Fig. 43.—Curves A. Inductive Coupling of Antenna and Condenser Circuit with Balancing Capacity at one end of the Secondary Circuit of the Oscillation Transformer and Antenna attached to the other end.

Fig. 44.—Curves B. Inductive Coupling of Antenna and Condenser Circuit with one end of Secondary Circuit of Oscillation Transformer earthed and Antenna attached to the other.

the latter case being when the fundamental natural oscillation time period of the antenna agrees with that of the condenser circuit (see Fig. 45).

In connection with this part of the subject the reader may be referred to an interesting paper by Mr. J. E. Ives, on the "Wave Lengths and Overtures of a Linear Electrical Oscillator." See *Physical Review*, vol. 30, February, 1910.

The case to which the chief technical interest attaches, however, is that in which the natural free time period of the condenser circuit

agrees either with the fundamental natural free period of the coupled antenna or with a harmonic of the latter, the coupling not being very close, that is, the "coefficient of coupling," k, being not greater than 0·5.

We have already considered the theory of this disposition (see Chap. III. § 11). It is implicitly contained in the theoretical discussion of the Tesla coil, with capacity in each circuit, given by Oberbeck [24] and others, and has been treated by G. Seibt [25] with special reference to electric wave telegraphy.

Let us consider first the case of an antenna earthed through the secondary circuit of an oscillation transformer having a certain coefficient of coupling k (see Fig. 46). Let the primary circuit contain a condenser of capacity C_1, and let the equivalent inductance of the primary circuit when in presence of the secondary circuit of the oscillation transformer, but with the antenna and earth removed, be denoted by L_1. Then let C_2 be the capacity of the antenna with respect to the earth, and L_2 the equivalent inductance of the antenna and secondary circuit of the oscillation transformer. Let M be the mutual inductance of the two circuits of the transformer, and V_1 and V_2 the maximum values of the potential differences of the primary and secondary circuits, and I_1 and I_2 the currents in them, considered as vectors. If, then, we assume that the oscillations are undamped, that is, that the resistances of the two circuits are negligible, we may write the vector equations connecting potential and current for the two circuits as follows:—

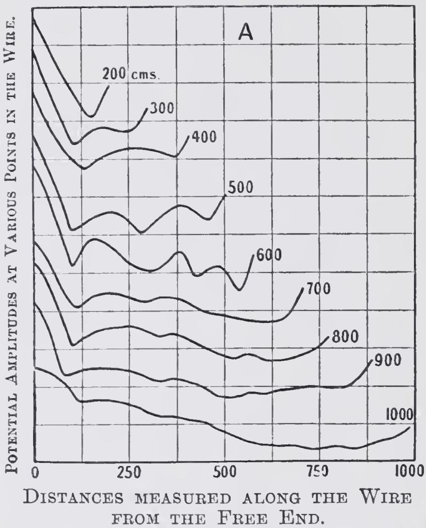


Fig. 45.—Chant's Curves representing the Potential Distribution in an Antenna Wire coupled directly to a Condenser Circuit, with a Balancing Capacity instead of Earth Connection to the latter.

$$V_1 + jpL_1I_1 + jpMI_2 = 0 \quad . \quad . \quad . \quad . \quad . \quad (30)$$

$$V_2 + jpL_2I_2 + jpMI_1 = 0 \quad . \quad . \quad . \quad . \quad . \quad (31)$$

$$\text{also} \quad I_1 = jpC_1V_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

$$I_2 = jpC_2V_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Then, eliminating from the above equations I_1, I_2, V_1, and V_2, we have—

$$p^4 - p^2\frac{C_1L_1 + C_2L_2}{C_1C_2(L_1L_2 - M^2)} + \frac{1}{C_1C_2(L_1L_2 - M^2)} = 0 \quad . \quad (34)$$

[24] See A. Oberbeck, *Wied. Ann. der Physik*, 1895, vol. 55, p. 627.

[25] See G. Seibt, *Physikalische Zeitschrift*, August 1, 1904; or *L'Éclairage Électrique*, October, 1904, vol. 41, p. 2.

Hence, solving this quadratic (34)

$$p^2 = \frac{1}{2C_1C_2(L_1L_2 - M^2)}\left\{(C_1L_1 + C_2L_2) \pm \sqrt{(C_1L_1 - C_2L_2)^2 + 4C_1C_2M^2}\right\} \quad (35)$$

Suppose, then, that the oscillation constants of the antenna and condenser circuits are made equal by adjusting the capacity and inductance, so that $C_1L_1 = C_2L_2 = CL$. Then the above solution for p^2 reduces to—

$$p^2 = \frac{1}{CL} \cdot \frac{1 \pm k}{1 - k^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

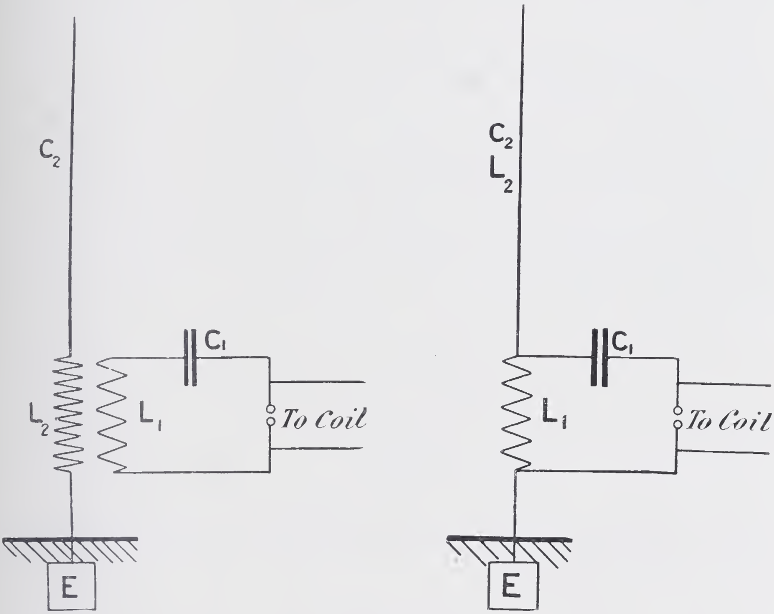


FIG. 46.

Antenna and Condenser Circuit Inductively Coupled. Antenna and Condenser Circuit Directly Coupled.

C_1, condenser; L_1, inductance; E, earth plate; C_2, antenna.

where $k = \frac{M}{\sqrt{L_1L_2}}$. Since $p = 2\pi n$, we may write the solution in the above critical case as follows:—

Let n_0 denote the natural frequency of each circuit alone, so that $n_0 = \frac{1}{2\pi\sqrt{CL}}$; also let p_1 and p_2 be the two roots of the equation (36), and let $p_1 = 2\pi n_1$, and $p_2 = 2\pi n_2$.

Then we have from (36)—

$$\left.\begin{aligned} n_1 &= n_0 \frac{1}{\sqrt{1-k}} \\ n_2 &= n_0 \frac{1}{\sqrt{1+k}} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

It follows that—

$$\left.\begin{aligned} n_0^2 &= \frac{n_1^2 + n_2^2}{2} \\ k &= \frac{n_1^2 - n_2^2}{n_1^2 + n_2^2} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

These equations show us that if k has any value less than unity, and if the open and closed circuits have the same oscillation constant when separate, then when coupled together the oscillation set up in the open circuit is a complex oscillation, which is composed of two oscillations of different frequencies, n_1 and n_2. The more nearly k approaches to unity, the greater will be the difference between n_1 and n_2 and the difference of either of them from n_0.

Since the length λ of the wave radiated from the antenna is connected with the frequency n of the oscillations in the antenna by the equation $u = n\lambda$, where u is the velocity of radiation, viz. 3×10^{10} cms. per second, or 10^9 feet per second, it follows that there are two waves of wave length λ_1 and λ_2 radiated from the tuned inductively coupled aerial, and these wave lengths are connected with the natural fundamental wave length λ_0 of the antenna and associated secondary transformer circuit, and with the coefficient of coupling k by the equations—

$$\left.\begin{aligned} \lambda_1 &= \lambda_0\sqrt{1 - k} \\ \lambda_2 &= \lambda_0\sqrt{1 + k} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

$$2\lambda_0^2 = \lambda_1^2 + \lambda_2^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

$$\text{and} \quad k = \frac{\lambda_2^2 - \lambda_1^2}{\lambda_2^2 + \lambda_1^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (41)$$

Again, since the wave lengths of the radiated waves are proportional to the equivalent oscillation constants O, we may write the equations (40) and (41) in the form—

$$2O_0^2 = O_1^2 + O_2^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)$$

$$k = \frac{O_1^2 - O_2^2}{O_1^2 + O_2^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

Also we can calculate the relative energy of the two secondary oscillations of frequency, n_1 and n_2. For the secondary current has a maximum value I_2, and therefore a maximum energy $\frac{1}{2}L_2I_2^2 = W$. But $I_2^2 = C_2^2V_2^2p^2$ by (33). Therefore $W = C_2L_2\left(\frac{C_2V_2^2}{2}\right)p^2$.

Since C_2L_2 is the square of the oscillation constant (O^2) of the antenna, we see that—

$$W = O^2p^2\left(\frac{C_2V_2^2}{2}\right)$$

Again, by (36) there are two values of the product O^2p^2, viz. $\frac{1}{1-k}$ and $\frac{1}{1+k}$.

If, then, W_1 and W_2 are taken to denote the maximum energies of

the two resultant oscillations of frequency, n_1 and n_2, we have by (36) and (37)—

$$\frac{W_1}{W_2} = \frac{1+k}{1-k} = \frac{n_1^2}{n_2^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

or the oscillation which has the greatest frequency has the greatest energy.

The above deductions from theory can be experimentally confirmed by means of the author's cymometer. The following are the details of an experiment made with an inductively coupled antenna at the Pender Laboratory of University College, London, which will illustrate the facts.

The antenna consisted of four aluminium wires each 50 feet in length, arranged fan-shape, the wires being 5 feet apart at the top, and at the bottom joined to a copper bar from which proceeded a thick stranded copper cable bent rectangularly, and in all 23 feet long. The bottom of this antenna was attached to one terminal of the secondary circuit of an oscillation transformer, consisting of a length of 45 feet of 7/22 copper wire, wound in nine turns on a square wooden frame. The other end of this secondary circuit was earthed. The total length of antenna from earth to summit was 118 feet. The antenna was arranged as in Fig. 39. The total capacity was 0·000538 mfd. A cymometer was then placed with its copper bar parallel to a portion of the antenna, and a pair of spark balls inserted between the oscillation transformer and the earth, so as to form a simple Marconi aerial. Using the cymometer as described, the oscillation constant O_0 of this antenna was found to be 6·9. Hence the equivalent inductance L_2 of the antenna and associated transformer circuit was 88,500 cms., for $C = 0{\cdot}000538$, and $(6{\cdot}9)^2 = \frac{538}{10^6} \times 88500$.

The primary circuit of the oscillation transformer consisted of one turn of about 6 feet in length of a massive conductor made of seven lengths of 19/22 copper cable, arranged in parallel, wound over the secondary circuit.

This primary circuit was connected in series with a spark-ball discharger and a glass-plate condenser, having a total capacity of 0·0357 mfd. This closed circuit had its capacity C_1 adjusted, so that in connection with the inductance L_1 of the above thick circuit and connectors the circuit had an oscillation constant of 6·9, equal to that of the antenna circuit. Hence we have $L_1 = 1330$ cms. When the oscillations were created by connecting the spark balls to an induction coil as usual, and the antenna oscillations tested by the cymometer, it was found that there were two oscillation periods in the antenna, showing that it was radiating waves of two wave lengths. The cymometer gave readings for the two oscillation constants, viz. $O_1 = 8{\cdot}5$ and $O_2 = 5$, corresponding to radiated æther waves of 1000 feet and 1700 feet in wave length.

$$\text{Hence} \quad O_0 = 6{\cdot}9 \qquad O_1 = 8{\cdot}5, \quad \text{and } O_2 = 5$$
$$\text{also} \quad O_0^2 = 47{\cdot}6, \quad O_1^2 = 72{\cdot}2, \text{ and } O_2^2 = 25$$

The condition to be fulfilled is—

$$2O_0^2 = O_1^2 + O_2^2 \text{ or } \frac{(O_1^2 + O_2^2)}{O_0^2} = 2$$

and we see that—

$$\frac{72{\cdot}2 + 25{\cdot}0}{47{\cdot}6} = 2{\cdot}04$$

instead of being exactly equal to 2·0, as it should be. The difference from theory is only, however, 2 per cent. The correctness of the above formula connecting the values of O, O_1, and O_2 has been also confirmed by the experiments of C. Fischer (see *Annalen de Physik*, vol. 22, p. 265, 1907, or *Science Abstracts*, vol. x. A., 1907, *abs.* 702).

Furthermore, the coefficient of coupling k of the oscillation transformer should be given by—

$$k = \frac{O_1^2 - O_2^2}{O_1^2 + O_2^2} = \frac{72{\cdot}2 - 25{\cdot}0}{72{\cdot}2 + 25{\cdot}0} = 0{\cdot}49$$

In Chap. II. § 4, and Chap. VI. § 16, we have already given direct measurements of the coefficients of coupling of similarly constructed oscillation transformers, and shown that k has a value not far from 0·5. Hence the value deduced from the above cymometer readings is likely to be right.

Again, since the lengths of the two waves of the radiated waves are $\lambda_1 = 1700$ feet, and $\lambda_2 = 1000$ feet, the natural wave length λ_0 of the free independent antenna should be $\frac{(1700)^2 + (1000)^2}{2} = 1400$ feet, and this agrees with the measurement of the free oscillation constant 6·9, for the radiated wave length is always nearly 200 times the oscillation constant of the antenna.

We see again, therefore, how erroneous it is to assume that for such a coupled aerial the radiated wave length is four times the total height of the antenna, *plus* the length of its associated inductance coil. For the antenna, if coupled so as to be in syntony with the condenser circuit, radiates two waves of different wave lengths, neither of them related to the height of the aerial by the simple fourfold relation.

These wave trains possess different maximum amplitude and different damping or decrements, and to this matter we shall revert again presently.

3. *The Oscillations in a Directly Coupled Antenna.*—A large number of electric wave telegraph stations are equipped with transmitters consisting of a condenser, spark gap, and inductance in series with each other, one end of the inductance coil being earthed and the other connected to an antenna. The condenser and spark gap are in series, and placed as a shunt across the inductance (see Fig. 46).

Following an investigation of G. Seibt,[26] we shall first determine the relation between the constants of the circuit and the frequency. Let C_1 be the capacity of the primary condenser, and L_1 the inductance of the coil in series with it. Let L_2 be the inductance of the antenna, and C_2 its capacity with respect to the earth.

Let I_1 be the current through the condenser, I_2 the current into the antenna, and I_1' the current in the inductance coil. Let V be the potential difference of the terminals of the inductance, or of those of

[26] See G. Seibt, *Physikalische Zeitschrift*, August 1, 1904; or *L'Éclairage Électrique*, October 1, 1904, p. 27, "A Comparison between the Direct and Inductive System of Coupling in Transmitters for Wireless Telegraphy."

the condenser. Lastly, let $p = 2\pi n$, and $j = \sqrt{-1}$, as usual. We have, then, the following vector equations:—

$$\left.\begin{aligned} \mathrm{V} &= jp\mathrm{L}_1 I_1' \\ \mathrm{V} &= -j\frac{I_1}{p\mathrm{C}_1} \\ \mathrm{V} &= jI_2\left(p\mathrm{L}_2 - \frac{1}{p\mathrm{C}_2}\right) \\ \text{also} \quad I_1 &+ I_1' + I_2 = 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

Eliminating the symbols for current and potential, we have a biquadratic in p, viz.—

$$p^4 - p^2\frac{\mathrm{C}_2\mathrm{L}_2 + \mathrm{C}_2\mathrm{L}_1 + \mathrm{C}_1\mathrm{L}_1}{\mathrm{C}_1\mathrm{C}_2\mathrm{L}_1\mathrm{L}_2} + \frac{1}{\mathrm{C}_1\mathrm{C}_2\mathrm{L}_1\mathrm{L}_2} = 0 \quad . \quad . \quad (46)$$

Since the above expression has unequal roots, it indicates that oscillations of different frequencies are set up in the antenna.

Suppose that the length of the antenna is so adjusted that its own free oscillation constant is the same as that of the condenser circuit taken alone, then we shall have—

$$\mathrm{C}_1\mathrm{L}_1 = \mathrm{C}_2(\mathrm{L}_1 + \mathrm{L}_2) = \mathrm{CL}, \text{ say}$$

Under these conditions the solution of the biquadratic (46) becomes—

$$p^2 = \frac{1}{\mathrm{C}_2\mathrm{L}_2}\left(1 \pm \sqrt{\frac{\mathrm{L}_1}{\mathrm{L}_1 + \mathrm{L}_2}}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

$$\text{or} \quad p = \sqrt{\frac{1}{\mathrm{C}_2\mathrm{L}_2}\left(1 \pm \sqrt{1 - \frac{1}{1 + \frac{\mathrm{L}_1}{\mathrm{L}_2}}}\right)} \quad . \quad . \quad . \quad . \quad (48)$$

$$\text{but} \quad \frac{1}{\mathrm{C}_2\mathrm{L}_2} = \frac{1}{\mathrm{CL}}\left(1 + \frac{\mathrm{L}_1}{\mathrm{L}_2}\right)$$

$$\text{hence} \quad p = \sqrt{\frac{1}{\mathrm{CL}}\left(1 + \frac{\mathrm{L}_1}{\mathrm{L}_2}\right)\left(1 \pm \sqrt{1 - \frac{1}{1 + \frac{\mathrm{L}_1}{\mathrm{L}_2}}}\right)} \quad . \quad (49)$$

Let us write in the above solution $\frac{1}{1 - \rho^2}$ instead of $1 + \frac{\mathrm{L}_1}{\mathrm{L}_2}$, and we then have as the solution in the syntonic case—

$$p = \sqrt{\frac{1}{\mathrm{CL}} \cdot \frac{1 \pm \rho}{1 - \rho^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (50)$$

$$\text{or} \quad n = \frac{1}{2\pi\sqrt{\mathrm{CL}}} \cdot \frac{1}{\sqrt{1 \pm \rho}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (51)$$

Hence there are oscillations of two different frequencies excited in the antenna. Call these frequencies n_1 and n_2, and let $n_0 = \frac{1}{2\pi\sqrt{\mathrm{CL}}}$

be the frequency of the condenser circuit or antenna alone. Then we have—

$$\left.\begin{aligned} n &= n_0 \frac{1}{\sqrt{1+\rho}} \\ n_2 &= n_0 \frac{1}{\sqrt{1-\rho}} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (52)$$

as the values of these frequencies.

Also, since $u = n\lambda$, where u is the velocity of the waves radiated from the antenna, we have—

$$\left.\begin{aligned} \lambda_1 &= \lambda_0 \sqrt{1+\rho} \\ \lambda_2 &= \lambda_0 \sqrt{1-\rho} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (53)$$

as equations giving us the wave lengths of the waves radiated, where λ_0 is the natural free fundamental wave length of the aerial.

On comparing the above equations (53) with the similar equations (39) for the inductively coupled antenna, we see that the quantity above called $\rho = \frac{\sqrt{C_2}}{\sqrt{C_1}}$ appears in the same place as the coefficient of inductive coupling k, and may hence be called the coefficient of direct coupling. Accordingly, if ρ is small, that is, if the antenna capacity is small compared with that of the condenser, only waves of one wave length are emitted from the antenna, but if the capacity of the antenna is of the same order as that of the condenser in the closed circuit, then two waves of different wave length will be emitted, as in the inductively coupled case.

The method of inductive coupling, however, gives a great range of adjustment, because we can without altering the capacity of the antenna or condenser vary k over wide limits by moving the two circuits of the oscillation transformer to or from each other.

As in the case of the inductive coupling, so in that of the direct coupling, when two different wave lengths are emitted in virtue of syntonism between the open and closed oscillating circuits, these two waves have different maximum intensities and different damping.

It is, however, not quite so easy to produce in a direct-coupled antenna oscillations of two frequencies, as in the case of an inductively coupled antenna. The reaction of the antenna on the energizing or reservoir circuit, on which this duplexing of the frequency depends, is less well marked in the case of the direct-coupled antenna than in the case of the inductively coupled one.

9. The Radiation from an Antenna.—When oscillations are set up in an antenna either by charging it directly and discharging it into the earth or into a balancing capacity, or else exciting them in it by inductive or direct coupling to an energizing circuit, part of the energy so given to the antenna is dissipated as heat in it, and part in the heat and noise of the spark, if any, in its circuit; whilst the remainder is radiated in the form of æther or electromagnetic waves. The consideration of the amount so radiated is important as it defines the efficiency of the antenna for radiotelegraphic purposes.

In the case of a plain directly charged antenna, the capacity of

the aerial is one of the factors which determine its energy-storing power, and hence its radiative effect; for if C is the antenna capacity reckoned in microfarads, and V is the potential to which it is charged (reckoned in volts), then the energy stored up in it before oscillations begin is equal to $\frac{CV^2}{2 \times 10^6}$ joules.

In the case of the single wire aerial with spark gap the value of the charging voltage can be determined from the spark length used. Thus, suppose we have a single-wire aerial 0·1 inch in diameter and 180 feet in length, used as a plain Marconi aerial with 1 cm. spark gap, we can calculate the energy storage as follows: The table on p. 673 shows that the capacity of such an aerial will be about 0·00035 mfd., and the table in Chap. II. p. 205, giving the dielectric strength of air, shows that the charging voltage will be about 30,000 volts. Hence the energy storage is—

$$\frac{0{\cdot}00035 \times (30000)^2}{2 \times 10^6} = 0{\cdot}157 \text{ joule}$$

or about 0·125 foot-pound.

Supposing this charging took place 50 times a second, as would be the case, perhaps, when using an ordinary induction coil, the power delivery is 8 watts. This power is partly dissipated as heat in the spark, and partly radiated as electromagnetic wave energy.

We have already given a formula for the ratio of these portions.[27] With a suitable cymoscope, such as a Marconi aerial and magnetic detector, this radiation could be detected at a distance of 100 miles or more when intercepted by a receiving antenna of the same height. This gives an idea of how exceedingly small an amount of energy is necessary to affect a suitable telegraphic cymoscope.

In the case of the simple aerial with single spark gap there is a limit to the charging voltage, which can be usefully employed. The resistance of the spark increases rapidly with its length, and hence, if we lengthen the spark gap, say, beyond a centimetre, the increase in damping begins greatly to decrease the efficiency of the antenna as a radiator. It is an advantage in some cases to employ multiple spark gaps with plain aerials, using, say, 4 or 5 spark gaps of a millimetre or less in series with each other.

It is also an advantage to act on the spark gap with a blast of air. This serves to destroy any true electric arc which may form, but does not hinder the condenser discharge. The particular conditions under which this air-blast is of use are set forth in a paper by the author and Mr. Richardson, entitled, "The Effect of an Air-blast upon the Spark Discharge in Condenser Circuits" (see *Phil. Mag.*, May, 1909), read before the Physical Society of London, March 26, 1909, in which it is shown that for short sparks, 1–3 mm. in length, the air-blast is an advantage, as it both increases the mean-square value of the oscillatory current and greatly steadies it.

In the case of an antenna not directly charged, but coupled inductively or directly to a reservoir circuit containing a condenser,

[27] For the expression for the efficiency of an antenna as a radiator, see Chap. III. § 7, equation (43).

the antenna has a much larger store of energy to draw upon. This is dissipated in several ways—

(i.) As heat in the spark in the primary circuit;
(ii.) As heat in the metallic portion of the primary condenser circuit;
(iii.) In the condenser in dielectric hysteresis and brush discharge;
(iv.) As heat in the antenna and antenna circuit, and perhaps at the earth plate;
(v.) As electric radiation from the antenna.

We can make an approximate estimate of the percentage of the stored energy which is radiated, as follows:—

Let us assume that the primary condenser has a capacity C_1 mfds., and is charged to a voltage V_1, as estimated from the spark length, and is discharged N times per second. Then the rate at which energy is given out by the condenser is $\frac{NC_1V_1^2}{2 \times 10^6}$ watts.

Let R'_1 be the high frequency resistance of the primary circuit, and r the resistance of the spark. Then, if L_1 is the inductance of the primary circuit, and δ_1 its resistance decrement, as modified by the presence of the secondary or antenna circuit, we have—

$$R'_1 + r = 4nL_1\delta_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

where n is the frequency.

In the same way, if δ_2 is the *resistance decrement* of the antenna circuit, and R'_2 its high frequency resistance, including in this any earth-plate resistance, if an earth connection is employed, we have[28]—

$$R'_2 = 4nL_2\delta_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

Let J_1 and J_2 be the R.M.S. values of the primary or condenser circuit currents and the antenna current respectively, this last being measured at the earthed end of the antenna. We can always determine these currents by the use of hot-wire ammeters inserted between the antenna and earth plate and in the condenser circuit. Accordingly, if we have in use a condenser in which we may fairly assume there is no dielectric loss, the difference between the power given out by the condenser and that dissipated as heat must be the power W radiated by the antenna. Hence the value of the expression—

$$W = \frac{NCV^2}{2 \times 10^6} - J_1^2\,4nL_1\delta_1 - \tfrac{1}{2}J_2^2\,4nL_2\delta_2 \quad . \quad . \quad (56)$$

gives us the radiation in watts, provided the earth-plate loss is negligible.

The factor $\frac{1}{2}$ is prefixed to the third term because the current varies up the aerial in accordance with a sine law, and is J_2 at the earthed end and zero at the summit of the aerial. Hence its mean square value is $\frac{1}{2}J_1^2$.

The frequency n is obtained from a measurement of the common oscillation constant of the two circuits.

The values of L_1 and L_2 are obtained when we know the capacities of the condenser in the primary circuit C_1 and that of the aerial C_2,

[28] It should be noted that we are not here concerned with the radiation decrement of the antenna.

for $C_1L_1 = C_2L_2 = O^2$ when the circuits are syntonized, O being the oscillation constant of either circuit.

If capacities are all measured in microfarads, inductances in centimetres, currents in amperes, and potentials in volts, the above expression for the rate of radiation of energy in watts is transformed into—

$$W = \frac{NC_1V_1^2}{2 \times 10^6} - \frac{O}{50}\left(\frac{J_1^2\delta_1}{C_1} + \frac{1}{2}\frac{J_2^2\delta_2}{C_2}\right). \quad . \quad . \quad . \quad (57)$$

The value of δ_1 will depend upon the spark gap length and capacity C_1 in the condenser circuit. The value of δ_2 will, in general, be small, since there is no spark gap in the antenna circuit, unless there is considerable dissipation of energy by earth-plate resistance, which ought not to be the case. The exact value of δ_1 can be obtained by means of a resonance curve, as already explained. For if we allow the condenser circuit to act inductively on another closed circuit of known resistance decrement, δ_3, we can, by varying the inductance of this last circuit, determine the sum of the decrements $\delta_2 + \delta_3$ by the resonance curve, and δ_3 being known, we thence find the value of δ_2. Thus, for instance, a primary circuit had in it a condenser of $\frac{1}{40}$ mfd., and a spark gap of 1·5 mm., charged 50 times per second. The oscillation constant was 7·0, and the energy of J_1 was 10 amperes. If, therefore, $\delta_1 = 0{\cdot}03$, we have for the power W, reckoned in watts, imparted to the coupled antenna, the value—

$$W = \tfrac{1}{2} \cdot \frac{36}{40} 50 - \frac{7 \times 3 \times 40}{50} = 5{\cdot}5 \text{ watts}$$

From this would have to be deducted the power loss due to the high frequency resistance of the antenna, and any earth-plate loss, and the balance is the power radiated. The problem of determining the radiation from an antenna may also be dealt with analytically as follows :—

We may consider the problem of determining the total radiation of a single wire antenna theoretically from first principles thus :— We have seen that in an antenna the current varies from point to point, and also the potential. We may then consider the antenna, however complicated, as made up of a number of elements, in each of which the current is approximately constant. Each of these elements will have a certain alternating potential difference between their ends, and may therefore be regarded as small Hertzian oscillators. The electric and magnetic force of the whole antenna is therefore the resultant of the forces due to each elementary oscillator separately. We have already given in Chap. V. § 7, the expressions for the electric and magnetic forces of a small Hertzian oscillator at points at a considerable distance from it, and also shown how the total radiation can be calculated by means of Poynting's theorem. Suppose we now consider a vertical linear plain antenna, and divide it up into Hertzian elements, each of length δz, and suppose a hemisphere described around it, the radius of which is very large compared with the height of the antenna (see Fig. 47). Then at any

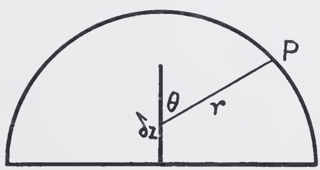


Fig. 47.

point P on the surface of this hemisphere we can calculate the electric and magnetic force due to the whole antenna as follows:—

We shall assume that the hemisphere is so large that lines drawn from any point on it to all points on the antenna make the same angle θ with the vertical. The expressions for the forces due to a small oscillator of electric moment ϕ at a point P, at a great distance r when the radius vector r makes an angle θ with the vertical are (see equations (31), Chap. V.)—

$$\left.\begin{aligned} Y &= -\frac{\phi m^2}{r}\sin\chi\sin\theta\cos\theta \\ Z &= \frac{\phi m^2}{r}\sin\chi\sin^2\theta \\ a &= \frac{\phi mn}{ur}\sin\chi\sin\theta \end{aligned}\right\} \quad \ldots\ldots \quad (58)$$

Now, by Poynting's theorem it is known that the whole energy sent out in a time dt from the element is (by (56), Chap. V.) equal to—

$$\frac{\phi^2 m^3 p}{2}\sin^2\chi\sin^3\theta\, d\theta\, dt$$

where $p = 2\pi$ times the frequency. Hence the energy sent out by the small oscillator per period is—

$$\frac{16\phi^2\pi^4}{3\lambda^3}$$

Suppose that i is the maximum current in any element of length δz of the antenna, and that ϕ is the maximum electric moment of this element during the period. Then it is easily seen that $i\delta z = \phi p$.

The maximum current at any point in the linear simple antenna may be expressed as a sine function of the position of δz in the form—

$$i = I\sin\frac{\pi}{2h}(h - z)$$

where h is the height of the antenna, and z is the distance of the point from the lower end, and I is the maximum current at the base or earthed end of the antenna. This expression gives us $i = I$ when $z = 0$, and $i = 0$ when $z = h$, as it should do.

If we then substitute the above values of ϕ and i in the equations for the electric and magnetic forces of the elementary oscillator, we have—

$$\left.\begin{aligned} Y &= -\frac{Im^2}{rp}\sin\frac{\pi}{2h}(h - z)\sin\chi\sin\theta\cos\theta\,\delta z \\ Z &= \frac{Im^2}{rp}\sin\frac{\pi}{2h}(h - z)\sin\chi\sin^2\theta\,\delta z \\ a &= \frac{IAm}{r}\sin\frac{\pi}{2h}(h - z)\sin\chi\sin\theta\,\delta z \end{aligned}\right\} \quad \ldots \quad (59)$$

To obtain the radiation of the whole antenna, we have to integrate the above expressions for the forces due to an element, z, of the antenna, along the entire length of the antenna or from 0 to h, and use these integral forces in obtaining by Poynting's theorem the total radiation.

Under the assumptions made this amounts to the same thing as substituting in the formula for the radiation of an elementary oscillator, viz. $w = \frac{16\phi^2\pi^4}{3\lambda^3}$, the proper equivalents for ϕ and λ for the whole antenna. These are easily seen to be $\phi = \frac{2hI}{\pi p}$ and $\lambda = \frac{u}{n}$ where p now denotes as usual 2π times the frequency n.

Accordingly, the energy radiated in ergs per period by the whole linear antenna is—

$$w = \frac{16h^2n}{3u}\left(\frac{I}{u}\right)^2$$

where I is the current at the base of the antenna in electrostatic units, and n is the frequency of the oscillations.

If we reckon the current in amperes, and denote it by A, we have $\frac{A}{10} = \frac{I}{u}$, and the radiation per complete period in ergs is—

$$w = \frac{16}{300}\frac{h^2n}{u}A^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (60)$$

Hence the rate of radiation, or radiation per second reckoned in *watts*, is—

$$\left.\begin{aligned} W &= \frac{160}{u^2}h^2n^2A^2 \\ &= 160\frac{h^2}{\lambda^2}A^2 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

In the case of single or multiple wire antenna oscillating freely there is a relation between the radiated wave length λ and the antenna length h, such that $\frac{h}{\lambda}$ varies between 0·25 and about 0·15, and may approximately be expressed by the equation $hn = \frac{u}{5} = 6 \times 10^9$, or $h^2n^2 = \frac{u^2}{25}$. In this case then—

$$W = \frac{160}{25}A^2 = 6{\cdot}4A^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (62)$$

If the current at the base of the antenna is varying, whether in persistent or in damped oscillations, we still have the mean radiation in watts, equal to 6·4 times the mean-square current in amperes.

We are therefore led to the curious result that the radiation from an antenna of the above type is independent of its height, and depends only upon the square of the current at the base or into the earth.

The formula (62) is quite consistent with that given in Chap. V. § 13 (75) for the radiation from a Hertzian linear oscillator. It was there proved, on the assumption that the current is the same at all points in the oscillator, that the radiation in watts is given by the formula—

$$W = 40\pi^2\frac{l^2}{\lambda^2}A^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (63)$$

where l is the total length of the Hertzian oscillator, and A is the current at the centre. If, instead of being the same at all points, the current varies from point to point according to a sine law, then we have to multiply the formula (63) by $\frac{4}{\pi^2}$. Also for the Hertzian oscillator the quantity $\frac{l}{\lambda} = 0{\cdot}4$ nearly, whereas for the vertical earthed antenna the equivalent quantity, viz. $\frac{hn}{u} = 0{\cdot}2$. Applying these two correcting factors, the formulæ (62) and (63) become the same.

It is quite possible to succeed in obtaining an expression for the radiation of an antenna of more complicated form by integrating the forces due to the Hertzian elements into which it may be divided, but the result would in any case show that the radiation in watts could be expressed as the product of some numerical factor C, and the square of the current at its base.

The practical determination of the *radiation efficiency* of a radiotelegraphic spark transmitter can be dealt with in the following manner. By radiation efficiency is to be understood the ratio expressed as a percentage which the power radiated by the antenna as electromagnetic waves bears to the power given to the transformer or induction coil which supplies it. At the present time we can only obtain this ratio by ascertaining carefully all the sources of power loss in the transmitter, and estimating the radiated power as a difference.

By means of a wattmeter, correct for low-power factor values, we can ascertain the mean power in watts given to the transformer or induction coil. Care must be taken that the wattmeter reads correctly on low-power factors. We have then to ascertain how this power is expended. We can measure in the usual manner the internal losses in the transformer due to copper resistance and iron core loss, and subtracting these, find the power given to the oscillation circuit. The next step is to determine the mean-square current in this primary oscillation circuit, which can be done by means of the author's thermoelectric high-frequency ammeter, and also the primary circuit decrement, which can be done by taking a resonance curve with the cymometer, as explained in Chap. III. During this measurement the antenna must be detached so that no radiation takes place. This decrement measurement should be made for various values of the current in the primary oscillation circuit.

The inductance of this circuit must also then be measured by the cymometer or by any other suitable means, and then from the primary decrement δ_1 and inductance L_1 we can calculate as above shown (see equation (54)) the power loss due to resistance. This measurement includes any loss in the condenser, because this loss proportionately increases the decrement. The sum of the internal losses in the transformer and that in the oscillation circuit being deducted from the power supplied, must give the power taken up by the antenna. The amount taken up in antenna resistance and by any earth-plate resistance can be ascertained by making a measurement of the high-frequency resistance by means of the differential electric thermometer described in Chap. II. of samples of the wire

used to make the antenna and oscillation transformer circuit in series with it and any connecting wires.

If the current I_2 in the antenna circuit is measured by a hot-wire ammeter inserted in it at various points, we can calculate the value of $\frac{1}{2}R_1'I_2^2$ for the whole antenna. There remains, then, the earth-plate resistance loss, if any. In the case of ships at sea this loss will be very small, but not altogether negligible in the case of stations on shore. It can, however, be determined by substituting for the earth plate a metallic capacity insulated from the earth, but which is sufficiently large to create the same mean-square current at the base of the antenna, and when these two last power losses are deducted from the total power given to the antenna, the difference must be the power radiated. Such measurements as have been made by this method show that the power actually expended in radiation in a spark transmitter is always small compared with the total power given to it. The actual percentage will vary considerably with apparatus and conditions, but it is probably near the mark to say that when using the spark transmitter creating damped waves, the actual power radiated by an ordinary inductively coupled antenna is not more than 10 per cent. of the power given to the exciting transformer, even if as much. For further information on this point, the reader may be referred to a paper by the author on "Quantitative Measurements in Radiotelegraphy," read to the Institution of Electrical Engineers of London, December 16, 1909 (see *Journal Inst. Elec. Eng.*, vol. 44, p. 344, 1910).

In connection with radiotelegraphy, it is important to notice that this radiated energy is not sent out equally in all directions.

If we describe round a Hertzian oscillator a spherical surface of radius r, large compared with the length of the oscillator, then we have shown that the radiant energy sent out by the oscillator per period, which passes through the surface of this sphere, is given by the formula $E = \frac{16\phi^2\pi^4}{3\lambda^3}$, where ϕ is the maximum electric moment of the oscillator and λ the radiated wave length.

The energy sent out through a zone of width $d\theta$ in time dt is equal to—

$$\frac{\phi^2 m^3 n}{2} \sin^3\theta\, d\theta \sin^2(mr - nt)dt \quad . \quad . \quad . \quad . \quad (64)$$

(see equation (56), § 9, Chap. V.). Hence the energy sent out through the zone per period is equal to—

$$\frac{\phi^2 m^3 n}{2} \sin^3\theta\, d\theta \cdot \frac{T}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

Bearing in mind that $m = \frac{2}{\lambda}$ and $n = \frac{2\pi}{T}$, and that the area of the zone is $2\pi r^2 \sin\theta\, d\theta$, it is easily seen that the energy radiated per period through each such elementary zone is expressed by—

$$\frac{4\phi^2\pi^4}{\lambda^3} \sin^3\theta\, d\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

Accordingly there is no energy radiated in the direction of the antenna itself, and it is a maximum in the equatorial plane.

If we plot out a curve such that its radii vectors drawn from a point are proportional to $\sin^3 \theta$, where θ is the colatitude angle, we obtain a curve having the shape shown in Fig. 48, which may be

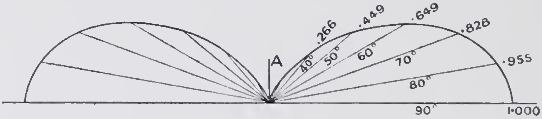


FIG. 48.

called a radiation curve. A curve of this kind was first given by Professor A. Blondel in 1903.[29] The numbers on the radii are the cubes of the sines of the angles θ taken from the table below.

θ	Sin θ	Sin^2 θ	Sin^3 θ
0	0·0	0·0	0·0
10	0·173	0·03	0·005
20	0·342	0·117	0·040
30	0·500	0·25	0·125
40	0·643	0·413	0·266
50	0·766	0·587	0·449
60	0·866	0·749	0·649
70	0·939	0·882	0·828
80	0·985	0·970	0·955
90	1·000	1·000	1·000

Now, the surface of the enclosing sphere is $4\pi r^2$, and hence the mean spherical energy radiated per period is given by—

$$\frac{E}{4\pi r^2} = \frac{4\phi^2\pi^3}{3r^2\lambda^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (67)$$

This corresponds to the mean spherical candle-power of an arc lamp.

This energy is not, moreover, radiated equally in all directions. If we divide the surface of the sphere into narrow zones, bounded by lines of latitude having angular distances or colatitudes θ and $\theta + d\theta$ respectively, we have seen that the energy passing through each such zone per period is given by equation (66). Accordingly, the radiation per square unit of area for each zone is obtained by dividing $\frac{4\phi^2\pi^4}{\lambda^3} \sin^3 \theta \, d\theta$ by the area of the zone $= 2\pi r^2 \sin \theta \, d\theta$, and is therefore equal to—

$$\frac{2\phi^2\pi^3}{r^2\lambda^3} \sin^2 \theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (68)$$

Since the mean value of $\sin^2 \theta$ for uniform distribution over a sphere

[29] In a paper entitled, "Quelques Remarques sur les Effets des Antennes de Transmission," at the meeting of the French Association for the Advancement of Science at Angers in 1903.

is $\frac{2}{3}$, the formula (68) agrees with (67), viz. that for the mean spherical energy radiation.

If in (68) we put $\theta = 90°$ we find the mean horizontal energy radiation per period per unit of surface to be $\frac{2\phi^2\pi_3}{r^3\lambda^3}$.

It is seen, therefore, that the mean horizontal energy radiation which passes through unit of area of the sphere per period in the equatorial plane is equal to 1·5 times the mean spherical energy radiation per period per unit of area.

Accordingly, in considering the energy available for absorption by the receiving antenna, we have to deal with this horizontal radiation density, and not with the mean spherical radiation density as many writers have done.

It is therefore a peculiarly valuable quality of the linear antenna, or earthed vertical antenna as used in radiotelegraphy, that it sends out its energy chiefly in the direction in which it is desired to be sent out, viz. along the surface of the earth, and not up into the sky or equally all round the hemisphere. Professor Blondel pointed out in 1903 (*loc. cit.*) that this quality of vertical antenna, however, renders it incapable of communicating with a balloon nearly overhead, and limits very much the power of such an antenna to radiate usefully to a receiving station on any aerial vessel overhead or high up above the horizon.

A matter of considerable importance is the relation between the height or length of an antenna and the wave length of the waves radiated from it. This has been experimentally examined with great care by M. Ferrié (see M. C. Tissot, "Étude de la Résonance des Systèmes d'Antennes dans la Telegraphie sans fil." Gauthier-Villars. Paris, 1906). If the total length of the antenna is denoted by h, and if λ is the wave length of the radiation, then M. Ferrié states that $\frac{\lambda}{4h}$ is always slightly less than unity for simple single wire antennæ, and the ratio increases for multiple branched antennæ.

M. Tissot shows, however, that the ratio $\frac{\lambda}{4h}$ is always greater than unity, and approaches unity as the antenna length increases, so that for a very long single line antenna the wave length radiated is four times the length of the antenna. For branched or multiple antenna the ratio $\frac{\lambda}{4h}$ is notably greater than unity. For a four-branched antenna at University College, London, the author found the value of $\frac{\lambda}{4h}$ to be 1·25, which makes the wave length equal to five times the length of the antenna.

In the case of inductively coupled antennæ, if we include the length of the secondary wire of the oscillation transformer inserted in series with the antenna in the total length, then the ratio $\frac{\lambda}{4h}$ may rise as high as 1·7 or 1·8.

10. The Damping of the Oscillations in an Antenna.—We have seen that some forms of cymoscope, such as the metallic filings coherer, are chiefly affected by the maximum value of the first wave impinging on it. Others, such as the bolometer cymoscope, indicate the root-mean-square value of the oscillations in the wave trains, and some, like the magnetic detectors, are influenced both by the maximum oscillation and by the number of oscillations. Hence a very important matter in connection with practical electric wave telegraphy is the rate at which the wave amplitude decays during the emission of a wave train from the antenna. This is determined by the logarithmic decrement of the oscillator.

If we consider first the case of the simple linear earthed oscillator or Marconi aerial with spark gap at the earthed end, we have already seen that the total decrement Δ is made up of two parts, (i.) the radiation decrement δ_r, (ii.) the resistance decrement δ_s, and if the antenna is a plain or Marconi antenna having a spark gap in it, this last may be divided again into that due to the wire and that due to the spark resistance.

Let R′, as usual, be the high frequency resistance of the wire, R being its ohmic or steady resistance, and let r be the resistance of the spark. Let C be the capacity of the aerial, and L its inductance for high-frequency currents. Finally, let l be the length of the antenna and d its diameter, both expressed in centimetres. We have already shown that the radiation decrement δ_r for a single straight wire antenna is given by—

$$\delta_r = \frac{1{\cdot}25}{\log_\epsilon \frac{2l}{d}} \text{(per half-period)} \quad . \quad . \quad . \quad . \quad (69)$$

(see Chap. III. § 5, equation (35a)), and that the resistance decrement is given by—

$$\delta_s = \frac{R' + r}{4n\mathrm{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (70)$$

(see Chap. III. § 5, equation (19)). The value of R′ for a copper wire of length l and diameter d cms. for a frequency n is approximately—

$$R' = 80\frac{l}{d}\sqrt{n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

(see Chap. II. § 1).

Again, the high frequency inductance L of the straight antenna of length l and diameter d has been shown to be—

$$\mathrm{L} = 2\left(\log_\epsilon \frac{4l}{d} - 1\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (72)$$

We have, then, to substitute for $\sqrt{n}$ in the formula for R′ its value in terms of l and d.

M. Abraham has shown (see *Wied. Ann.*, 1898, vol. 66, p. 435) that for a linear wire oscillator of length l and diameter d, earthed at the lower end, the frequency n of the fundamental oscillation is given by the expression—

$$n = \frac{3 \times 10^{10}}{4l(1 + 5{\cdot}6\rho^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (73)$$

$$\text{where} \quad e = \frac{1}{4 \log_\epsilon \frac{2l}{d}}$$

For a wire 50 metres high and 5 mm. in diameter, $5{\cdot}6e^2 = 0{\cdot}007$. But for a Marconi aerial wire the frequency of the fundamental oscillation n is approximately $\frac{u}{4l}$, and $\sqrt{n} = \frac{1}{2}\sqrt{\frac{u}{l}}$. Substituting these values for n and $\sqrt{n}$, R′ and L in the expression for δ_s, we arrive at a complete expression for the total decrement per half-period Δ as follows:—

$$\Delta = \frac{1{\cdot}25}{\log_\epsilon \frac{2l}{d}} + \frac{40\sqrt{l}}{2d\sqrt{u}\left(\log_\epsilon \frac{4l}{d} - 1\right)} + \frac{r}{2u\left(\log_\epsilon \frac{4l}{d} - 1\right)} \quad . \quad (74)$$

where $u = 3 \times 10^{10}$ and r is the spark resistance in ohms.

The first term on the right-hand side is that part of the total decrement due to radiation, the second that part due to wire resistance, and the third term that part due to spark resistance. Generally speaking, the second term is small compared with the other two, and especially compared with the first term.

For example, suppose we consider the case of a copper wire aerial 50 metres long and 5 mm. in diameter, the wire section being circular. Then $l = 5000$ cms., $d = 0{\cdot}5$ cm. If we assume a spark resistance $r = 5$ ohms, we have the following values for the component and total decrements per semi-period, viz.—

$$\Delta = 0{\cdot}125 + 0{\cdot}0015 + 0{\cdot}008 = 0{\cdot}135$$

The first term is the radiation decrement, the second the decrement due to wire resistance, and the third that due to spark resistance.

If we refer to the formula (Chap. III. §§ 3, 18) for the number of semi-oscillations, m, in a train of given decrement, viz.—

$$m = \frac{4{\cdot}605 + \Delta}{\Delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (75)$$

and substitute for Δ the total decrement $0{\cdot}135$ just obtained for the antenna in question, we obtain the value $m = 35$, which shows that seventeen or eighteen complete oscillations would take place at each discharge of this antenna before the maximum of the oscillations is reduced to 1 per cent. of the initial amplitude.

Let us consider next the case of the inductively coupled antenna. We have shown that when the condenser circuit and open or antenna circuit are isochronous, or have the same independent time-period when separate, two sets of oscillations of different frequencies are set up in these circuits when they are coupled together.

These two vibrations have different damping or decrements. Let δ_1 and δ_2 denote the decrements of the two coupled circuits when separate and far apart from each other. We have then two cases to consider.

(i.) When the coupling coefficient k is extremely small, or the coupling weak.

(ii.) When k has a moderately large value approaching unity, or the coupling strong.

The predetermination of the decrements of the two oscillations set up in the antenna is then more difficult, and the theoretical formulæ so far given do not agree with the results of experiment. The problem has been theoretically treated by M. Wien and also by P. Drude.

If we call D_1 and D_2 the decrements per half-period of the two secondary oscillations, when the coupling coefficient k is so small that $\frac{(\delta_2 - \delta_1)}{\pi k}$ is large compared with k, the following expressions have been given by M. Wien.[30]

$$D_1 = \tfrac{1}{2}\left\{(\delta_1 + \delta_2) + (\delta_1 - \delta_2)\sqrt{1 - \frac{\pi^2 k^2}{(\delta_1 - \delta_2)^2}}\right\} \quad . \quad . \quad (76)$$

$$D_2 = \tfrac{1}{2}\left\{(\delta_1 + \delta_2) - (\delta_1 - \delta_2)\sqrt{1 - \frac{\pi^2 k^2}{(\delta_1 - \delta_2)^2}}\right\} \quad . \quad . \quad (77)$$

and if $\frac{\pi k}{(\delta_1 - \delta_2)}$ is small compared with unity, these expressions reduce to—

$$D_1 = \delta_1 + \frac{\pi^2 k^2}{4(\delta_2 - \delta_1)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (78)$$

$$D_2 = \delta_2 - \frac{\pi^2 k^2}{4(\delta_2 - \delta_1)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (79)$$

Hence the sum of D_1 and D_2 is equal to the sum of δ_1 and δ_2, but the D_1 is greater than the closed circuit decrement, and D_2 less than the open circuit decrement, so that the two resultant decrements lie in between the two independent ones. The wave of shortest wave length has a decrement greater than that of the condenser circuit alone, and the wave of longest wave length has a decrement less than that of the antenna taken alone.

When the coupling is fairly close, and the value of πk large compared with $(\delta_2 - \delta_1)$, P. Drude has shown[31] that D_1 and D_2 are connected with δ_1 and δ_2 and the frequencies by the equations—

$$D_1 = \frac{\delta_1 + \delta_2}{2} \cdot \frac{n_1}{n_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (80)$$

$$D_2 = \frac{\delta_1 + \delta_2}{2} \cdot \frac{n_2}{n_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (81)$$

where n_1 and n_2 are the frequencies of the two resultant oscillations, and n_0 is that of each circuit when separate.

From the above equations, it appears that *the oscillation which has the greatest frequency or shortest wave length should have the largest decrement.*

$$\text{Since} \quad \frac{n_1}{n_0} = \frac{1}{\sqrt{1 - k}}$$

$$\text{and} \quad \frac{n_2}{n_0} = \frac{1}{\sqrt{1 + k}}$$

[30] See M. Wien, *Ann. Phys.*, 1902, vol. 8, p. 696.
[31] See P. Drude, *Ann. der Physik*, 1904, vol. 13, p. 528, equation 119.

$$\text{we have}\quad D_1 = \frac{\delta_1 + \delta_2}{2\sqrt{1-k}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (82)$$

$$D_2 = \frac{\delta_1 + \delta_2}{2\sqrt{1+k}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (83)$$

Thus, suppose an inductively coupled antenna has a coefficient of coupling $k = 0{\cdot}5$, and that the condenser circuit alone has a resistance decrement $\delta_1 = 0{\cdot}02$, whilst the open circuit has a decrement $\delta_2 = 0{\cdot}2$ alone. If the two circuits are adjusted to have the same time period when separate, and then coupled together, we have two oscillations excited in the open circuit with decrements D_1 and D_2. Since $1 + k = 1{\cdot}5$, and $1 - k = 0{\cdot}5$, the above formulæ give—

$$D_1 = 0{\cdot}11\sqrt{2} = 0{\cdot}15$$

$$\text{and}\quad D_2 = 0{\cdot}11\frac{\sqrt{2}}{\sqrt{3}} = 0{\cdot}09$$

both of which are less than the open circuit decrement δ_2, and both greater than that of the closed circuit decrement δ_1, when these circuits are far apart. The closer the coupling, therefore, the more we approach the condition of a single wave emission with small damping radiated from the antenna. If we could make $k = 1$, we should have one single oscillation frequency with decrement D, such that—

$$D = \frac{0{\cdot}11}{\sqrt{2}} = 0{\cdot}08$$

Experiment does not, however, confirm this theory.

This matter has already been discussed in Chap. III. § 14, in reference to the experiments of C. Fischer, who showed that the above formulæ given by Drude are not even qualitatively correct, as it is not true in general that the oscillation with the highest frequency has the largest decrement.[32] On the contrary, Fischer's experiments proved that over a large range of coupling the reverse was true, viz. that the oscillation which has the lowest frequency of the two has the largest decrement or damping. In other words, it is the longer wave of the two which is most damped or has fewest oscillations in its train. Also the actual values found are larger than those predicted by Drude's formulæ. The comparison of theory and experiment is indicated in the curves in Fig. 37, Chap. III. It is seen that according to the theory given by Drude the values of the decrements of the two oscillations for various couplings should follow a linear law, but one increasing and the other diminishing. The decrement values given by observation, taken by Fischer by the method described in Chap. III. § 14, do not lie on straight lines, and are not nearly coincident with the theoretical lines. Fischer examined also the effect of varying the coupling from weak to very strong on the secondary current and found it somewhat complicated.

He also examined the effect of varying the coupling on the maximum amplitude and on the R.M.S. value of the secondary

[32] See C. Fischer, "On Coupled Condenser Circuits," *Annalen der Physik*, vol. 22, p. 265, 1907; or *Science Abstracts*, vol. x. A., 1907, *abs.* 702.

current. It was found that the amplitude first increased very rapidly with increased coupling, then became slightly less and then increased again. The greater the damping the flatter was the curve and less well defined the maximum and also the greater the coupling required to produce it.

In the case of radiotelegraphy conducted with an inductively coupled transmitter we may regard the receiving antenna as forming a tertiary circuit in reference to the two circuits of the transmitting antenna. Fischer experimented therefore with three closed circuits to represent this case.

He found that the maximum current in the tertiary circuit which represented the receiving antenna was reached with a very small coupling between the primary and secondary circuits of the transmitter. The larger the damping in the secondary and tertiary, that is, in the sending and receiving antennæ, the closer must be the coupling in the transmitter. All the results show that there is a certain limit to the closeness of coupling of the transmitter, and that to exceed this diminishes the current in the receiving antenna. It is found by experience that in the receiving circuits, if an oscillation transformer is employed, the two circuits must be loosely coupled to secure sharply marked resonance or tuning. Also in the transmitter, if inductive coupling is employed, a value of k not much exceeding 0·1 or 0·2 is found most advantageous.

11. The Coupling and Excitation of the Oscillations in an Antenna.—In modern radiotelegraphy the simple or plain self-excited Marconi antenna is now hardly ever used. The energy storage of the antenna itself is small and the oscillations set up on discharge are therefore quickly damped out. In practice the antenna is connected either directly or inductively with an energizing circuit, in which a much larger store of energy can be accummulated and then given up to the antenna as required. When the inductive coupling is used a two-coil oscillation transformer is interposed, one circuit of which is in series with the antenna and the other with the energizing circuit, and in the case of the so-called direct coupling a single coil or auto-transformer is employed. In both cases the two coupled circuits are syntonized together.

The general theory of the operation of such transformers when both circuits have condensers attached to their terminals has been given in a previous chapter (see Chap. III. § 14).

In the case of an oscillation transformer used in the transmitting apparatus, the circuit which contains the spark gap and the smaller of the two inductances, and therefore the larger of the two capacities, is called the primary circuit, whilst the other is called the secondary circuit. When employed to create oscillations in an antenna, the secondary circuit of the transformer is connected between the antenna and the earth, or else a large capacity called the balancing capacity replaces the earth. If the antenna is insulated and symmetrical, the secondary circuit is inserted in the centre.

It is found that no advantage ensues from winding the primary circuit of an oscillation transformer used in connection with a transmitting antenna with more than one turn of wire. The inductive effect of the primary circuit depends on the magnetic field it creates.

This, again, is the result of the ampere-turns of the primary current. The current in this circuit is chiefly determined by the inductance of the primary circuit, and the effect of increasing the turns on the primary circuit is, on the whole, to decrease the ampere-turns, since the inductance varies as some power of the number of turns lying between 1 and 2.

Accordingly, Mr. Marconi constructs his "transmitting jiggers" or oscillation transformers for use with sending aerial wires with one, or at most two, turns in the primary circuit. These may be made, however, of several single turns arranged in parallel.

The secondary circuit generally consists of more than one turn—say five to twenty turns—wound under or over the primary circuit. Very good insulation must be secured between the two circuits, and it is necessary to immerse the whole coil in a vessel of insulating oil.

A convenient mode of construction is to make two square frames of wood, each side about 50 cms. in length, and the width being 5 to 10 cms.

On one frame highly insulated and well-stranded copper wire is wound, a large number of strands being employed in parallel, each being taken once round the frame. The wire should be high conductivity copper wire, size No. 40 S.W.G., each wire slightly insulated with varnish, and a large number of these insulated wires, say 200, twisted together and insulated over all with indiarubber, and then again a sufficient number of these compound wires laid in parallel once round the frame and the ends soldered to copper strips.

In this manner we construct a circuit with low high-frequency resistance and also small inductance. On the other frame a sufficient number, say 5 to 10 turns, of well-insulated fine-stranded wire of the same kind are wound, and the two frames placed side by side in highly insulating transformer oil in a stoneware (not metal) vessel. When joined respectively in series with the condenser of the energizing circuit and with the antenna, the two circuits of the transformer can be tuned together by a supplementary inductance coil placed on one or other circuit.

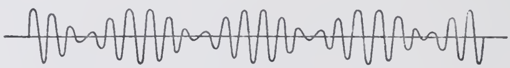
In practice it is advisable to employ oscillation transformers both in the transmitting and receiving apparatus, which permit the coupling to be varied over wide limits by altering the distance of the primary and secondary circuits. As regards the transmitter, this is best achieved by winding the primary and secondary circuits on separate square wooden frames, which are put together in one stoneware vessel of insulating oil if a close coupling is required, or in separate vessels separated from each other by a certain distance if a weak coupling is required. In the case of the receiving circuit where a high insulation is not required, the author has found that the best way of achieving it is to wind the two circuits in flat spirals on the surfaces of two hinged boards, so that they can be approximated or removed from each other by opening or closing the boards, more or less like a book. This plan is not practicable in the case of the transmitter, because very high insulation is necessary, and the two circuits must in general be immersed in transformer oil.

We have seen that when the two circuits of an oscillation transformer are syntonized, or have the same oscillation constant ($\sqrt{CL}$)

when separate, then when associated together inductively the potential differences created at the terminals of the condensers on the primary and secondary circuits are in the ratio of these capacities, and not in the ratio of the number of turns on the two circuits of the oscillation transformer.

Also we have seen that oscillations of two frequencies are then set up in the circuits. We may consider that the two circuits are like two pendulums which are connected by an elastic connection.

If we stretch across a corner of a room a rather loose string, and hang on this string, a few inches apart, two similar metal rods about a yard in length, having bobs at the bottom, which may be painted red and blue for the sake of distinction, we have two pendulums which may be said to be coupled together (see Chap. III. § 9). If one of these rods is drawn on one side and allowed to vibrate in a plane perpendicular to the loose string, it will communicate jerks to the string, and set the other pendulum in vibration. In accordance with the third law of motion, it cannot impart motion to the other pendulum without losing some of its own. Accordingly, the motion of the first pendulum gradually decreases as that of the other increases, and very shortly we find the pendulum originally set



First Pendulum.

Second Pendulum.

Fig. 49.—Oscillations of a Pair of Coupled Pendulums.

swinging at rest, and the other vibrating. But this process is then reversed, and so each pendulum is alternately in vibration and at rest. If we were to take a trace of the vibrations of the two pendulums on a moving sheet of paper passing at right angles to their motions, it would be as represented in Fig. 49, each trace being a wavy sinoidal line, with amplitude alternately increasing and diminishing. If the change of maximum amplitude is a simple sine function of the time, we may write the equation to such a curve as that in Fig. 49 in the form—

$$d = \mathrm{A} \cos qt \sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (84)$$

where d is the displacement at any instant t, A is the maximum amplitude, and q and p are respectively 2π times the frequency of the beats and of the oscillations. This function, however, is equal to—

$$\tfrac{1}{2}\mathrm{A} \sin(p+q)\,t + \tfrac{1}{2}\mathrm{A} \sin(p-q)t \quad . \quad . \quad . \quad (85)$$

or may be resolved into the sum of two vibrations, one greater and one less in frequency than those of the pendulums taken alone. This waxing and waning of the amplitude is in the analogous case of acoustics described as the production of beats. Exactly the same

thing happens in the electrical case, viz. two coupled electric circuits, and we can not only resolve the complex vibration which then occurs in each circuit mathematically into two constituent components, but we can by means of the oscillograph tube, and the cymometer, actually see the electrical beats, and detect or measure the wave length of the two components.

If we connect a Gehrcke oscillograph vacuum tube (see Chap. I. § 6, Fig. 33) to the terminals of the condenser or across parts of the inductance of the secondary circuit, then, as explained already, the length of the glow light on the electrodes of the vacuum tube will vary proportionately to their potential difference. If, then, the tube is examined in a rapidly revolving mirror, making from 50 to 100 turns per second, the recurrent images of the glow light will be separated out, and we shall see a series of bright lines of greater or less lengths which denote the varying currents or potential differences in secondary circuit.

If we examine in this way the oscillations in a primary circuit with secondary circuit removed, we see an image consisting of a series of decreasing lines which is the single damped oscillation in the circuit (see Fig. 34, Chap. I.). If, however, the secondary circuit is closed, then the image is as represented in Fig. 22, Chap. III., which are from photographs taken by Herr Hans Boas of Berlin.

This last photograph shows the electrical beats in the secondary oscillation, the gradually increasing and diminishing oscillations being the result of the superposition of two sets of oscillations of different frequencies.

The same electrical beats are well shown in the photographs of the oscillations in coupled circuits, taken by Professor Taylor Jones (see Fig. 20, Chap. III.), with a mirror oscillograph of his own invention (see *Phil. Mag.*, August, 1907, p. 238), which represents the oscillation train in the form of a wavy line imprinted on a photographic plate, the ordinate of the line at any point representing the periodic potential difference between two points on the oscillatory circuit.

The effect of varying the closeness of the coupling (k) in an oscillation transformer is best shown by drawing a series of resonance curves with various couplings. When the two circuits are syntonized, but the coupling is very weak, we have seen that in the secondary circuit there is an oscillation of one single frequency of the common period. If then we make slight variations in the natural frequency of the secondary circuit by varying its inductance, and observe the current (R.M.S. value) J_2 in that circuit, and compare it with the maximum or resonance value $J_{2\,\max}$, we can plot a resonance curve of which the ordinates are the ratio $\left(\frac{J_2}{J_{2\,\max}}\right)^2$, and the abscissæ are the ratio $\frac{n_2}{n_1}$ of the frequencies in the secondary and primary circuits. We shall then have a curve with a single maximum (see Fig. 50). If the closeness of coupling is increased, we shall find that we obtain a resonance curve having two maximum ordinates differing in absolute value, and the curve resulting from the plotting of $\left(\frac{J_2}{J_{2\,\max}}\right)$ in terms of $\frac{n^2}{n_1}$ has a double hump (see Fig. 50).

Again, if we increase the value of k still more, we get a curve with two widely separated humps of different height, showing that there are two frequencies corresponding to two maximum values of the

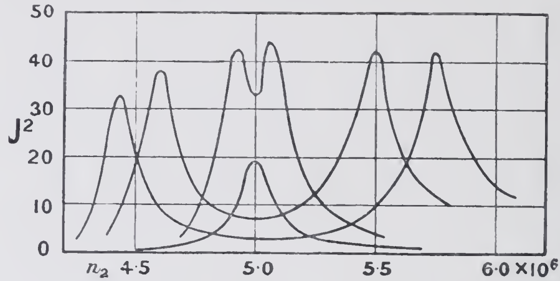


FIG. 50.—Resonance Curves for Various Degrees of Closeness of Coupling of Primary and Secondary Oscillation Circuits. The curve with single maximum corresponds to very loose coupling, and the curves with double maximum to various degrees of close coupling of the circuits.

secondary current. Thus the more we increase k the wider apart and the higher do these two maxima of antenna current lie. We have already shown (see Chap. III. § 14) that the ordinate y of the resonance curve, where $y = \left(\frac{J_2}{J_{2\,max}}\right)^2$, is connected with the sum of the decrements δ_1 and δ_2 of the two circuits separately by the equation—

$$\delta_1 + \delta_2 = \pi\left(1 - \frac{n_2}{n_1}\right)\sqrt{\frac{y}{1 - y}} \quad . \quad . \quad . \quad . \quad (86)$$

and it follows that—

$$y = \left(\frac{J_2}{J_{2\,max}}\right)^2 = \frac{\left(\frac{\delta_1 + \delta_2}{\pi}\right)^2}{\left(1 - \frac{n_2}{n_1}\right)^2 + \left(\frac{\delta_1 + \delta_2}{\pi}\right)^2} \quad . \quad . \quad . \quad (87)$$

Since, then, there are two values of the frequency of the secondary circuit for which resonance occurs, which are more widely separated, the greater k (see equation 37), it follows that there must be two maximum values of the ordinate of the resonance curve.

As an illustration of the application of the foregoing formula, we may give the following measurements made with a transmitting plant set up in the Pender Laboratory at University College, London. The antenna is inductively connected, through an oscillation transformer having a coefficient of coupling 0·5, with a condenser circuit having a capacity of 0·025 mfd. and an inductance of 2000 cms. The antenna circuit is syntonized with the condenser circuit separately, so that each has the same oscillation constant when uncoupled. We have then $k = 0{\cdot}5$, $C_1 = 0{\cdot}025$ mfd., $L_1 = 2000$ cms. Hence the oscillation constant $\sqrt{C_1L_1} = 7{\cdot}07$, and the frequency n_0 in the condenser circuit taken alone is—

$$n_0 = \frac{5 \times 10^6}{\sqrt{C_1L_1}} = \frac{5}{7} \times 10^6$$

Hence the corresponding wave length λ_0 is 1400 feet, since the velocity of radiation is 10^9 feet per second nearly. Accordingly, we have $\sqrt{1+k} = 1{\cdot}224$ and $\sqrt{1-k} = 0{\cdot}707$, and the two wave lengths emitted by the coupled aerial have values λ_1 and λ_2, such that—

$$\lambda_1 = \lambda_0\sqrt{1-k} = 1400 \times 0{\cdot}7 = 980 \text{ feet}$$

$$\lambda_2 = \lambda_0\sqrt{1+k} = 1400 \times 1{\cdot}224 = 1714 \text{ feet}$$

To sum up, then, the effects taking place in the case of the inductive coupling of two oscillatory circuits both having capacity, inductance, and resistance, are as follows:—

If the circuits are nearly syntonized, that is, have nearly the same oscillation constant or time period of oscillation when free and separate, then when coupled inductively, and oscillations created by discharge in one circuit, we have in the other circuit a complex oscillation which may be analyzed into the sum of a forced oscillation and a free oscillation. These combine to produce a resultant oscillation with periodic maxima resembling the effect of *beats* in music, and this, again, may be analyzed into the sum of two oscillations of different frequencies. Nevertheless, the resultant oscillation has a single definite mean-square or effective value given by the expression—

$$J^2 = \frac{E_2}{16L_2^2}\cdot\frac{a_1+a_2}{a_1a_2}\cdot\frac{1}{4\pi^2(n_1-n_2)^2+(a_1+a_2)^2} \quad . \quad . \quad (88)$$

where E is the maximum electromotive force acting in the secondary circuit of inductance L_2, and a_1 and a_2 are the damping factors, such that $a_1 = 2n_1\delta_1$ and $a_2 = 2n_2\delta_2$, δ_1 and δ_2 being the decrements of the two circuits when separate (see Chap. III. § 14).

If I_1 is the maximum value of the primary current in the condenser circuit, then $E = Mp_1I_1$ where M is the coefficient of mutual inductance. But $I_1 = C_1V_1p_1$, and $M = k\sqrt{L_1L_2}$, also $p_1^2C_1L_1 = 1$; accordingly—

$$E^2 = k^2L_1L_2C_1^2V_1^2p_1^4 = k^2C_1V_1^2L_2p_1^2$$

$$\text{or} \quad \frac{E^2}{L_2^2} = \frac{k^2V_1^2}{L_1L_2}$$

Therefore we have—

$$J^2 = \frac{k^2V_1^2}{16L_1L_2}\cdot\frac{a_1+a_2}{a_1a_2}\cdot\frac{1}{4\pi^2(n_1-n_2)^2+(a_1+a_2)^2} \quad . \quad (89)$$

The maximum value of J takes place when $n_1 = n_2$, or when the circuits are in resonance. Denoting this resonance value of the mean-square current by $J^2_{\max}$, we have—

$$J^2_{\max} = \frac{k^2V_1^2}{16L_1L_2n^3}\cdot\frac{1}{\delta_1\delta_2(\delta_1+\delta_2)} \quad . \quad . \quad . \quad . \quad (90)$$

Since $C_1L_1n_1^2 = \dfrac{1}{4\pi^2}$, the above equation may be written—

$$J^2_{\max} = \frac{\pi^3k^2}{L_2p}\cdot\frac{C_1V_1^2}{2}\cdot\frac{1}{\delta_1\delta_2(\delta_1+\delta_2)} \quad . \quad . \quad . \quad . \quad (91)$$

This shows us that the maximum or resonance value of the secondary or antenna mean-square current is proportional to the energy storage

in the primary circuit, and inversely as the reactance of the secondary circuit, and determined also by a function of the decrements.

When the circuits are in resonance we have also $C_2L_2p^2 = 1$ and $n = \frac{5 \times 10^6}{O}$, where O is the common oscillation constant of the two circuits. If then we reckon the primary and secondary capacities C_1 and C_2 in microfarads, the primary voltage V_1 in volts, and the inductances in centimetres, and remember that π^4 is nearly 100, the expression for J^2_{max} may finally be put in the form—

$$J^2_{max} = \frac{k^2}{1000} \cdot \frac{C_2}{O} \cdot \frac{C_1V_1^2}{2} \cdot \frac{1}{\delta_1\delta_2(\delta_1 + \delta_2)} \quad . \quad . \quad . \quad (92)$$

Thus, suppose an inductively coupled antenna has a capacity $C_2 = 0{\cdot}0005$ mfd., and that the primary circuit contains a condenser of capacity $C_1 = 0{\cdot}025$ with a spark gap of 2 mm. Then $V_1 = 8000$ volts. Let the oscillation constant, when the circuits are tuned, be $O = 5$, corresponding to a frequency of $n = 10^6$. Further, let $k = 0{\cdot}5$, $\delta_1 = 0{\cdot}04$, $\delta_2 = 0{\cdot}1$. The mean-square value of the antenna current will then be—

$$J^2_{max} = \frac{1}{4{\cdot}10^3} \cdot \frac{1}{10^4} \cdot \frac{8{\cdot}10^5}{56} \cdot 10^5 = 36 \text{ nearly}$$

or the antenna current will be 6 amperes nearly.

To secure this high value, exact resonance is necessary. A very little want of tuning will reduce this antenna current considerably. If I_2 is the maximum value of the first oscillation of current in the antenna, and if there are N groups of oscillations per second, we have already shown (Chap. III. § 1) that—

$$J_2^2 = \frac{NI_2^2}{8n\delta}$$

Suppose in the above case that $N = 50$, or 50 condenser discharges are made per second, then $8n\delta_2 = 8 \times 10^5$, and I_2 has a value of nearly 780 amperes. This calculation shows us the enormous currents which may exist at certain instants in a perfectly tuned antenna, inductively coupled to a syntonic condenser circuit, and also by inference the extremely high potentials which may exist at the open or upper end. For an infinitesimal fraction of a second the aerial is carrying a current which would more than suffice to melt it if continued.

The value of the mean-square current in the antenna can always be ascertained by inserting in it a hot-wire ammeter, or else a bundle of a number of No. 36 platinoid wires, and ascertaining of how many strands this bundle must be composed, so that the wires may be melted or made red-hot.

The value of the maximum potential $V_{2\,(max)}$ at the upper end of the antenna can be obtained from that of the maximum value of the current in the following manner. Since the energy stored in the antenna is alternately electrostatic and electrokinetic, if L_2 is the antenna inductance and C_2 the capacity, we must have—

$$L_2I_2{}^2{}_{(max)} = C_2V_2{}^2{}_{(max)} \cdot \quad . \quad . \quad . \quad . \quad . \quad . \quad (93)$$

$$\text{Hence} \quad V_{2(max)} = I_{2(max)}\sqrt{\frac{L_2}{C_2}} = I_{2(max)} \cdot \frac{O}{C_2}$$

Thus, to take the above instance, we have found that $I_{2(max)} = 780$ amperes for the antenna with oscillation constant of 5 and capacity $C_2 = 0{\cdot}0005$ mfd.

$$\text{Therefore} \quad V_{2(max)} = 780 \frac{5 \times 2000}{\sqrt{1000}} = 260{,}000 \text{ volts (nearly).}$$

The $\sqrt{1000}$ is a factor to adjust the units, so that whilst potential and current are reckoned in volts and amperes, capacity is reckoned in microfarads, and inductance in centimetres.

Hence the voltage at the upper end of this antenna, when in resonance, would be equivalent to about a 9-cm. spark. Wireless telegraphists are all aware of the extremely long sparks which can sometimes be drawn from the upper end of antennæ. In the case of a large power plant, with which the Author is acquainted, sparks 7 feet long, corresponding, perhaps, to seven million volts, have been drawn from the upper end of the antenna. This shows the necessity for high insulation at the supporting insulator.

It will be seen, therefore, that in the case of a sending antenna inductively coupled to its energizing circuit, the radiated energy is divided between two sets of waves of different wave length and damping. As the receiving antenna is in general only tuned to pick up one of these sets of waves, a loss of radiant energy takes place. It has, therefore, been suggested that the receiving antenna should have two sets of receiving apparatus connected to it, one tuned to one wave length and the other to the other wave length emitted by the sending antenna, as illustrated in Fig. 51. Suggestions to this effect were made by the author in the first edition of this book, published in May, 1906, and also by J. Hettinger in October, 1906 (see *Electrical Engineer*, October 26, 1906), as well as by G. Seibt.

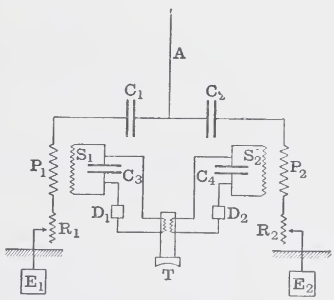


FIG. 51.

A method of exciting the oscillations in the antenna has, however, been devised in Germany which is called the method of excitation by shock or impact (*Stosserregung*), which results in the production of oscillations of only one frequency in the antenna.

Attention was called in 1906, by Professor M. Wien, of Danzig, to the extremely large damping in oscillatory circuits containing a spark gap of very short length.[33] If a primary oscillation circuit contains a very short spark gap or series of spark gaps and is coupled to a secondary circuit, then when oscillations are set up in the usual way by connecting the spark balls to an induction coil or transformer, the oscillations set up in the primary are quenched or damped out almost at once. On the other hand, the oscillations set up in the secondary circuit continue freely and with a single period. By passing, therefore, a very rapid number of quenched

[33] M. Wien, *Physikalische Zeitschrift*, No. 23, December, 1906, p. 872.

primary sparks, we can set up in the secondary circuits similar rapidly recurring prolonged trains of single-period (monotone) oscillations.

Under these conditions the primary circuit discharge imparts a shock or impulse to the secondary circuit, which results in setting up the free oscillations of the secondary circuit. The primary oscillations are damped out or quenched after a few oscillations, and hence the reaction between the primary and secondary oscillations, which results in the production of oscillations of two periods, is prevented. The course of events in the two circuits in the case of the ordinary primary spark, and the quenched spark or series of quenched sparks, is represented in the diagrams in Fig. 52.

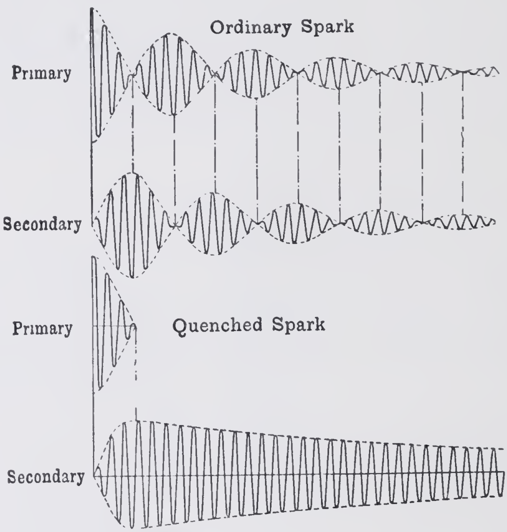


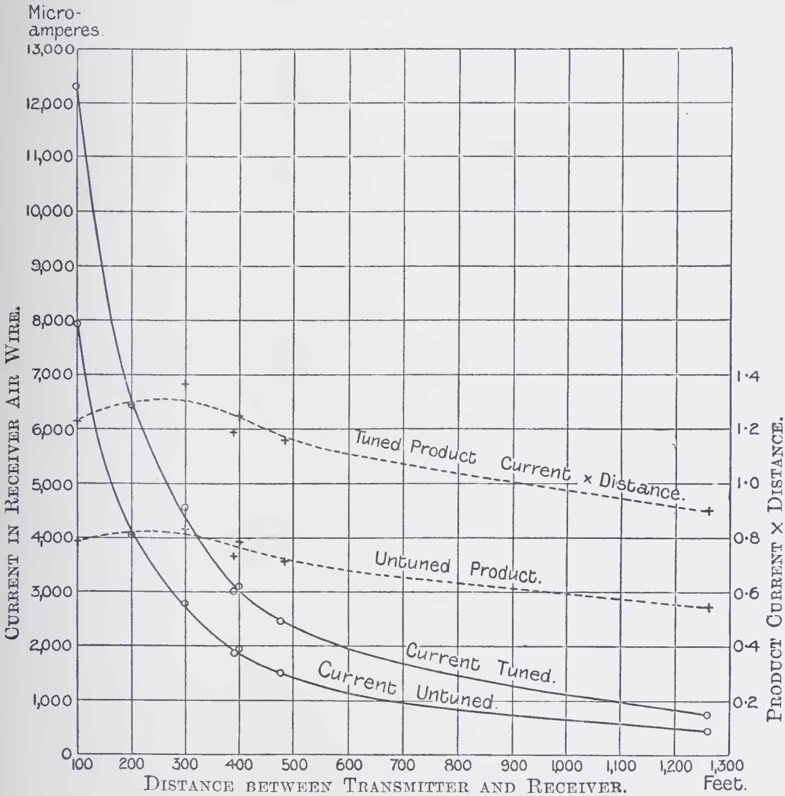
Fig. 52.—Diagram showing the Electrical Beats produced in the Primary and Secondary Circuits when a sustained Primary Spark is used, and the Single Period Oscillations in the Secondary Circuit when a Quenched Spark is employed.

The particular form of discharger used to produce this effect is described in a later section on dischargers.

12. Variation of Radiation Intensity with Distance and Height of Antenna.—Hertz showed, as we have seen (see Chap. V. § 7), that at a distance from a Hertzian linear oscillator, large compared with its wave length, the electric and magnetic forces vary nearly inversely as the distance from the oscillator. In the case of a closed circuit oscillator, however, the forces vary nearly inversely as the cube of the distance. It is this property of the open linear oscillator which, combined with its large radiative power, has made radiotelegraphy possible.

Since the energy of the wave varies as the square of the amplitude of the forces, the wave energy at any point varies inversely as the square of the distance from the transmitter. The law according to

which the field of an open vertical oscillator varies has been experimentally investigated by Messrs. Duddell and Taylor.[34] They operated with direct-coupled antennæ, and measured with a Duddell thermal ammeter the current in the receiving antenna. They used a wave stated to be 400 feet in wave length, but which was probably somewhat longer, and they measured the current with the Duddell thermal ammeter (see Fig. 31, Chap. VI.) both in an antenna



From the "Journal of the Institution of Electrical Engineers."

FIG. 53.—Curve showing the Variation of R.M.S. Value of the Current in the Receiving Antenna as the Distance between the Transmitter and Receiver is varied. From experiments by Messrs. Duddell and Taylor.

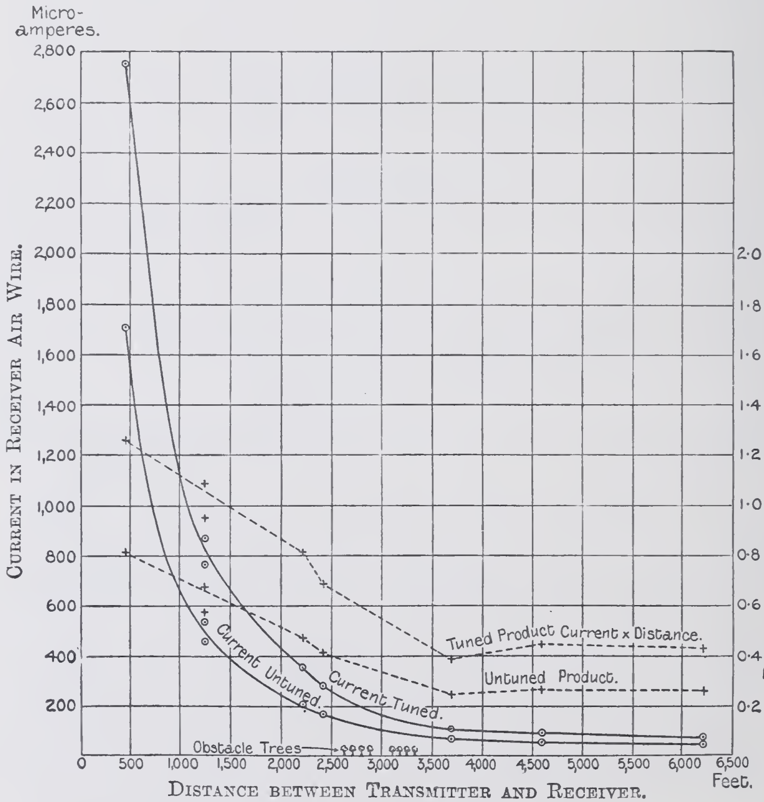
untuned and in one tuned to the incident wave. The results of some of their observations, giving the distances between the stations in feet and the R.M.S. value of the current near the base of the receiving antenna in microamperes in the case of the tuned and untuned antenna, are set forth in the following table, and graphically in the curves in Figs. 53 and 54.

[34] See "Wireless Telegraph Measurements," by W. Duddell and J. E. Taylor, *Journ. Inst. Elec. Eng. Lond.*, 1905, vol. 35, p. 321.

CURRENT IN THE RECEIVING ANTENNA WHEN DISTANCE BETWEEN THE SYNTONIC RECEIVER AND TRANSMITTER IS VARIED.

Height of Receiving Antenna, 56 feet. Height of Transmitting Antenna, 42 feet.

Distance in feet between antennæ.	Currents in antennæ.		Product of distance and currents in receiving antenna.
	Transmitter. Amperes.	Receiver. Microamperes.	
100	0·501	12320	1·232
200	0·507	6435	1·287
300	0·558	4548	1·364
400	0·541	3108	1·243
1260	0·541	715	0·901
2420	0·506	283·5	0·686
3700	0·517	105	0·388
4600	0·558	96·5	0·444
6220	0·563	69·5	0·432



F om the "Journal of the Institution of Electrical Engineers."

FIG. 54.—Curves showing the Variation of R.M.S. Value of the Current in the Receiving Antenna as the Distance between the Sending and Receiving Stations is varied. From experiments by Messrs. Duddell and Taylor.

The interposition of trees was found to affect the result law of variation sensibly, but the general result is to show that the currents in the receiving antenna varied rather more rapidly than it should have done in accordance with the law of inverse distance, but less rapidly than in accordance with the law of the inverse square of the distance. The curves clearly indicate that at close quarters the current in the receiver varies more rapidly than at greater distances. Within the distance of a wave length there is a very rapid decrease, which tends at much greater distances to come more nearly in accordance with the law of the inverse distance. This is quite in agreement with the deductions from Hertz's theory. He showed, as explained in § 7 of Chap. V., that for a linear oscillator the electric force at a great distance varies inversely as the distance from the oscillator, but that this law of variation does not hold good at relatively small distances. M. C. Tissot (see *The Electrician*, 1906, vol. 56, p. 848) has made similar experiments with a bolometer cymoscope inserted in the receiving antenna circuit, and confirmed the fact that the effective or R.M.S. value of the antenna current at the receiver station approximately varies inversely as the distance from the transmitting station.

13. Relation between Height of Antennæ and Maximum Signalling Distance. Marconi's Law.—Marconi enunciated at one time an empirical law that, for simple vertical sending and receiving antennæ of equal height, the maximum working telegraphic distance varied as the square of the height of the antennæ. It has been stated that the rule was tested in experiments made on Salisbury Plain in 1897.[35] Also by experiments made by Italian naval officers on behalf of the Royal Italian Navy in 1900 and 1901. Captain Quintino Bonomo has given a *résumé* of these last experiments in an official report.[36]

If H is the height of the antennæ and D the maximum good signalling distance in metres, then we have, according to Marconi's law—

$$H = c\sqrt{D}$$

where c is some constant.

Captain Bonomo gives the following values of c for various apparatus :—

c.	D in metres.	Nature of apparatus.
0·17 to 0·19	69,000	Marconi original apparatus, plain aerials.
0·15 ,, 0·16	69,000	Same, with longer sending spark.
0·12 ,, 0·14	136,000	Marconi improved apparatus, with jigger in receiver.
0·12 ,, 0·15	143,000	The same, but with Italian Navy telephonic receiver.

According to these results, antennæ having a height of 45 metres would enable communication to be established over 90 to 100 miles. This table must be taken to apply to oversea working.

In a *brochure* issued by the Allgemeine Elektricitäts Gesellschaft

[35] See a letter by Captain J. N. C. Kennedy, R.E., *The Electrician*, October 29, 1897, vol. 40, p. 22.

[36] See "Telegrafia senza fili," by Captain Quintino Bonomo, Rome, 1902, p. 26.

in 1902, describing the Slaby-Arco system, a curve is given (see Fig. 55), showing the height of aerials required for various distances

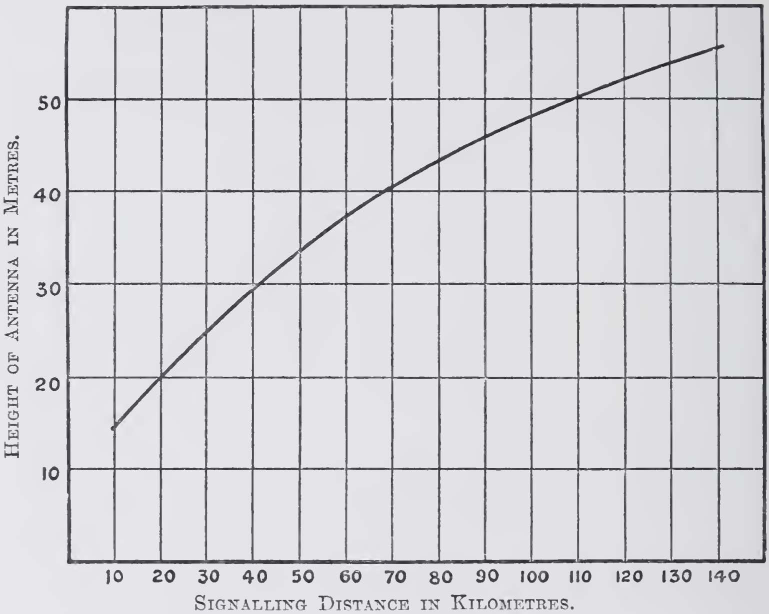


FIG. 55.—Curve showing the Relation between Height of Sending Antenna in Metres and Signalling Distance in Kilometres derived from the Experience of the General Electric Company of Berlin.

for oversea working. It will be seen that the curve approximately complies with the Marconi law. It is, however, expressly stated in the pamphlet that this curve cannot be applied to overland working. According to the curve given for the Slaby apparatus, the value of c varies from 0·14 to 0·16 when heights and distances are both measured in metres. This does not differ very greatly from the Italian Navy value of the same constant.

Marconi's law can be deduced theoretically as follows: Hertz has shown that at distances large compared with its length the magnetic force of a linear oscillator varies inversely as the distance (see Chap. V. § 7, equation 31). The maximum value of the current set up in any given receiving antenna varies as its length, also as the magnetic force of the waves incident on it, and as the maximum value of the current in the transmitting antenna. Hence, if M is the magnetic force of the waves incident on a receiving antenna of height H, and if D is the distance between the sending and receiving antenna, and if I_1 and I_2 are the maximum values of the currents in the sending and receiving antennæ, we have—

$$\mathrm{M} \propto \frac{I_1}{\mathrm{D}} \quad \text{and } I_2 \propto \mathrm{MH} \quad . \quad . \quad . \quad . \quad . \quad . \quad (94)$$

$$\text{Hence} \quad I_2 \propto \frac{I_1 \mathrm{H}}{\mathrm{D}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (95)$$

Also, since for a given charging voltage the current I_1 in the sending antenna varies very nearly as its capacity—that is, as its height—and if the sending antenna has the same height, H, as the receiving aerial, we have—

$$I_1 \propto \mathrm{H}$$

$$\text{But} \quad I_2 \propto \frac{I_1 \mathrm{H}}{\mathrm{D}}$$

$$\text{Therefore} \quad I_2 \propto \frac{\mathrm{H}^2}{\mathrm{D}} \propto \text{some constant}$$

For any given receiving apparatus a certain constant minimum value of the maximum current in the receiving antenna is necessary to cause a signal. Therefore it follows that, with given receiving and sending apparatus, we must have $\frac{\mathrm{H}^2}{\mathrm{D}}$ a constant, or—

$$\mathrm{H} = c\sqrt{\mathrm{D}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (96)$$

That is, the maximum signalling distance with given apparatus will vary as the square of the height of the antenna.

The above law is, however, much interfered with by the nature of the surface over which the propagation takes place.

14. The Function of the Earth in Radiotelegraphy.—We have seen that in initiating practical electric wave telegraphy, as contrasted with laboratory or short-distance experiments with electric waves, Marconi made this new method of telegraphic communication possible by erecting both at the sending and receiving stations a long vertical wire or antenna, the upper end of which was insulated, whilst the lower end was connected at the sending station to one of a pair or series of spark balls, the opposite ball or other end of the series being connected to an earth plate, whilst at the receiving station the wave-detecting device had one terminal put to the earth-plate, and the other to a similar antenna. The sending antenna was then as represented in Fig. 56 (*a*).

Subsequently other inventors inserted a large capacity or condenser, C, between the spark balls and the earth plate (see Fig. 56 (*b*)), and others adopted the use of a balancing capacity or counterpoise, B (see Fig. 56 (*c*)), consisting of a sheet of metal or network laid over the earth, but insulated from it. It cannot be considered that the insertion of the condenser between the earth plate and the spark balls makes any essential scientific difference, although it may be done for the purpose of contending that the antenna is not then actually earthed. If the conductively earthed antenna (*a*) is employed, then, as we have seen, the distribution of current in it must be such that there is a node of current at the upper end, and an antinode at the earthed end. In other words, currents must flow into and out of the earth plate and earth. If we sever the metallic connection to the earth plate and introduce a condenser of large capacity, we do not make any change in this respect. In place of a current of conduction we have a dielectric current through the condenser, and if its capacity is sufficiently large, this dielectric current may be as great as the current of conduction which flowed when the metallic conductor was

complete. Hence (*b*) is not different in principle from (*a*), and the antenna may with equal truth be said to be "earthed" at the lower end in both cases.

On the other hand, great differences of opinion exist whether the technical advantages lie on the side of the "earthed" antenna, or with the completely insulated antenna with balancing capacity (*c*). It is clear that in some cases the balancing capacity cannot be employed; for instance, on board ship, where there is no room for it. Hence, the hull of the vessel, making good earth, is invariably used. In other instances, such as large land stations, the necessary balancing

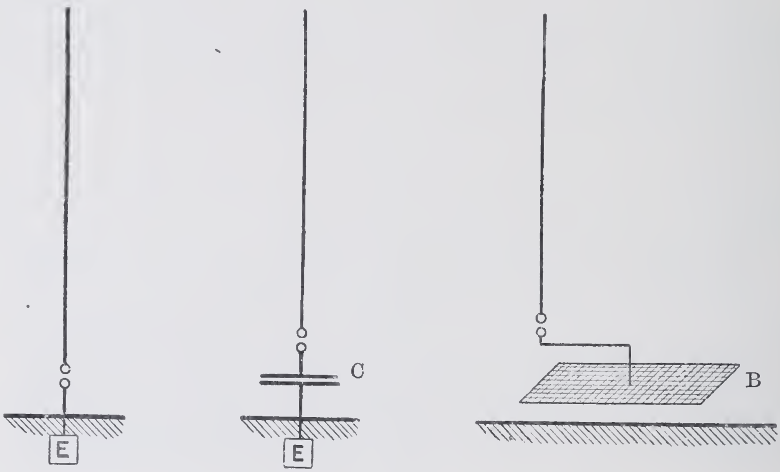


Fig. 56.—Various Modes of Connecting the Transmitting Antenna to the Earth. (*a*) By direct connection of the lower spark ball to an earth plate, E; (*b*) by connection through a condenser, C; (*c*) by a balancing capacity, B.

capacity, if used, would be very inconvenient owing to its size, in that it would impede access to the base of the towers or masts carrying the antenna, and necessitate a larger area of ground for working.

In the case of antennæ of very large size and capacity, such as those used for long distance stations, the size of the insulated balancing capacity required would make its use quite impossible. Hence it is, so to speak, put underground, in which case it becomes an earth plate.

There are a few cases in which the balancing capacity may be employed even if less convenient than the earth plate, provided some substantial advantage is derived by employing it. On this point the opinions of experts differ. Mr. Marconi, who introduced the earth connection, has always advocated it and employed it in all his stations. Other great practical authorities have agreed with him in the advantage or necessity for its use. In Marconi's fundamental British Patent, No. 12,039, of 1896, the 15th and 16th claims are as follows:—

15. A receiver consisting of a sensitive tube or other imperfect contact inserted in a circuit, one end of the sensitive tube or other imperfect contact being put to earth whilst the other end is connected to an insulated conductor.

16. The combination of a transmitter having one end of its sparking appliance or poles connected to earth, and the other to an insulated conductor, with a receiver as is mentioned in Claim 15.

The reference is to arrangements as shown in Fig. 2 of § 2 in Chap. VII. We have seen that the first demonstrations of electric wave telegraphy were obtained with this earthed system, and others who followed Marconi agreed with him in approving and employing it.

The following extract, taken from a paper by Admiral Sir Henry Jackson, endorses this opinion [37] :—

"A point of interest, which has also great effect on the signalling distance, is the efficiency of the earth connection of both the transmitting and receiving instruments. Fortunately for the system, on board a modern ship there is no difficulty in obtaining an almost perfect earth connection when the ship is at sea. In dry dock, however, there is, in fine weather, a great difficulty in doing so, and the effects of the bad earth with the ship in dock, on the signals, are extremely marked, both for transmitting and receiving, reducing the distance as low as to 25 per cent. of the distance with the ship afloat.

"A similar effect, due to drought, has been observed with some shore stations, where, according to my experiences, the maximum signalling distances have always been obtained during wet seasons of the year.

"A typical example is given :—

"On one particular occasion, towards the end of a very dry summer (last year), the maximum signal distance between a certain ship and station, 500 feet above the sea, was 38 miles, the usual distance having previously been 68 miles. Two days later, during which time no alterations whatever had been made to the adjustments of the instruments, but which included twenty-four hours of heavy rain, the maximum distance obtained was 70 miles, which has since been maintained.

"Repeated experiments with and without earths on the transmitter and receiver have shown that, in the open sea, signals may be obtained up to 50 or 60 per cent. of the full distance, without earths on the receiver, though such a large proportion is unusual, the average being 30 per cent. A condenser of suitable capacity acts nearly as well as a good earth; without an earth on the transmitter, the percentage of distance has never exceeded 15 per cent. Using good earths, but no aerial wire whatever on the receiver, or near it, signals have never been obtained over 3 miles. With no aerial wire on the transmitter, I have never known a signal to be received on board another ship over 2 miles distant.

"My experience demonstrates most clearly, and with no marked exception, that, for signalling any distance beyond a few miles, the combination of aerial wires and good earths is essential, for both transmitting and receiving instruments."

On the other hand, Sir Oliver Lodge has expressed strong opinions on the disadvantage of the direct connection of the antenna to earth, stating that the result of so doing is to damp out the oscillations set up in it sooner, and bestow on the trains of radiated waves a large decrement.[38]

He maintains that the earth connection is inimical to "good

[37] See Admiral Sir H. B. Jackson, R.N., F.R.S., "On Some Phenomena affecting the Transmission of Electric Waves over the Surface of the Sea and Land," *Proc. Roy. Soc. Lond.*, 1902, vol. 70, p. 254.

[38] See Sir Oliver Lodge and Dr. A. Muirhead, "On Syntonic Telegraphy," *Proc. Roy. Soc. Lond.*, vol. 82, A., p. 227, 1909.

tuning," which means to the production of prolonged trains of oscillations in the antenna. He says (*loc. cit.*), "If the earth were a perfect conductor it would presumably act like a mirror preventing the waves from spreading in that direction, and thereby doubling the intensity of any radiator above it; except that in certain places there would be liable to be interference bands where the difference between the source and the image was half a wave length. Such interference, however, chiefly occurs in the case of those long trains of waves appropriate for tuning. For single pulses—that is to say, the snaps needed for untuned signalling—the effect of a perfectly conducting earth would probably be good, and in so far as the sea is a moderately good conductor, connection with the sea may be advantageous for such signalling; but for tuned relation between the stations it is becoming clear that instead of prolonging the oscillations, its resistance wipes them out and kills them. It is far better to ignore the earth and work independently of it both at the sending and receiving end, taking care to keep everything insulated. We hereby gain the advantage of being independent of fluctuations in the quality of the soil in respect both of permanent geological quality and of variable heat and moisture, and we also get far better tuning.

"On the train of waves passing between distant stations the earth probably has no particular influence except by reason of its irregularities and obstruction; but over great distances it is possible they may be reflected advantageously in the good conducting regions of the upper atmosphere. But with extremely great distances Mr. Marconi has chiefly dealt. My object has been to perfect the tuning for moderate distances."

But these opinions, even although coming from a great authority on the scientific side of the subject, are not supported by the evidence of experience in practice. As already pointed out, a balancing capacity is impossible in the large majority of cases, ships and power stations, and very inconvenient even in large shore stations.

The opinion that the earth in between the sending and receiving station exercises no particular effect is directly negatived by the researches of J. Zenneck and Brylinski, and by the everyday experience of radiotelegraphists, who are well aware that a change in the state of moisture of the intervening region is accompanied by a change in the intensity of the received waves.

The basis for the above opinions are to be found in the paper published by Sir Oliver Lodge and Dr. Muirhead, in which experiments are described made between stations at Down and at Elmer's End in Kent, 7 miles apart. The station at Elmer's End sent out radiation of about 440 metres wave length, with an applied power of 400 watts. The station at Down received this on an aerial consisting of two capacity areas, each composed of four loops of wire on a horizontal plane, the centres being connected by a vertical wire. The upper area was elevated 60 to 67 feet above the earth, and the lower one at various heights above the earth. At the centre of the vertical wire was a receiving instrument which, in the case of these measurements, was a Duddell thermal ammeter.

A variable inductance or capacity was also inserted by means of which the receiving aerial could be put more or less out of tune with the

incident wave, and a resonance curve could then be plotted from the observed deflections of the thermal ammeter. It was found that when the lower capacity area was completely insulated and some way above the earth (even only 6 feet up), the resonance curve plotted out with a very sharp peak, thus indicating small damping both in the sending and receiving circuits. If, however, the lower capacity area was near to or on the earth, the resonance curve was flat and presented no well-marked peak. The experiments undoubtedly show that the earth at the receiving antenna does produce a sensible effect in damping the free oscillations set up in the receiving aerial, but they do not give proof that the earthing at the sending end is equally injurious. Nor do they prove that if the receiving or wave detecting instrument is inserted in a suitable closed oscillatory circuit inductively connected to the receiving antenna, that the damping out of the oscillations in the aerial wire will be equally accompanied by an equally quick damping out of the oscillations in the closed coupled circuit.

The conclusion of Sir Oliver Lodge and Dr. Muirhead that the earth connection is always a disadvantage is not supported by the opinions of other workers, who have carried out similar experiments with earthed and non-earthed antennæ. Thus J. S. Sachs,[39] in 1905, conducted experiments on the function of the earth in wireless telegraphy, in which he used Braun's form of apparatus, the energy transmitted and received being measured thermoelectrically. In some cases the stations were in resonance, and in others not. He came to the conclusion that the radiation from a system with an aerial and direct earth connection is three or four times greater than when the earth is replaced by a balancing capacity. He also tried the effect of raising the transmitter and receiver high above the ground, and found it an improvement. From these experiments he concluded that the earth between the stations exercises an absorptive action and does not much reflect the waves. He found that the energy received varies very approximately inversely as the square of the distance.

W. Burstyn (see *Science Abstracts*, vol. 10, B., 1907, *abs.* 222) also concludes, from a theoretical discussion of the influence of the size and position of the balancing capacity with respect to the earth, that unless the station is a small or temporary one, or built on hard dry rock, it is more economical to employ a direct earth connection. For military stations or those constantly moved about, he thinks it is better to employ a balancing capacity, as it ensures the equivalent of a good earth, and a proper earth connection cannot be obtained in dry sandy soil or very rocky ground. On the other hand, practical experience on a large scale does not give any warrant for the conclusion that the direct earth connection is always bad; on the contrary, long-distance work is impossible without it.

The reader may also be referred to a paper by Mr. Charles A. Culver in the *Physical Review*, for September, 1907, p. 200, entitled "A Study of the Propagation and Interception of Energy in Wireless

[39] See J. S. Sachs, "On the Function of the Earth in Wireless Telegraphy," *Elektrotechn. Zeitschr.*, vol. 26, p. 951, October, 1905; or *Science Abstracts*, vol. 8, B., 1905, *abs.* 1589.

Telegraphy," in which the writer examines the question of earth connection, and comes to the conclusion that "the earth plays a highly important part in the transmission of energy in wireless telegraph circuits, particularly the 'ground' at the transmitting station." He considers that the earth connection greatly increases the effect on the receiver. He even suggests that the effects at great distances are due to electrical disturbances, propagated through the earth's crust, and not directly to the effects of a free Hertzian wave through the space above it. There are, however, special difficulties connected with this view, though the abnormal diffraction of long radiotelegraphic waves round a quadrant of the earth's surface presents, on the other hand, difficulties in conceiving the effects due altogether to free ether waves.

The reader may also be referred to some quantitative experiments by Prof. C. Tissot (see "Résonance des Systèmes d'Antennes"), in which measurements were made with the bolometer receiver of the current in a receiving antenna, collecting radiation from a distant sending antenna. This last was so arranged that it could be connected at pleasure to various earth plates having a "bad" earth, a "dry" earth, and a "damp" and "very good" earth. The defections of the bolometer galvanometer were respectively 10, 26, 28, and 34 scale divisions, thus showing the improvement in the receiving antenna current with improvement in the "earth" at the sending end. Again, M. Tissot measured the receiving-end current when the earth plate was 1 metre square and 30 metres square, and found bolmeter defections respectively of 30 and 55 divisions. He also found that at the sending antenna under the same conditions the mean-square value of the current at the base of the antenna increased with the area of the earth plate at the sending end up to a certain area, whilst on board ship, where the contact with "earth," or rather sea, was perfect, the mean-square sending antenna current had a still larger value than for a similar transmitter on shore with an earth plate. His conclusion is that the earth connection absorbs a certain fraction of the energy imparted to the sending antenna.

As regards the use of a balancing capacity in place of the earth, the truth of the matter appears to be somewhat as follows. The radiation from a Hertzian antenna, as we have seen, is proportional to the mean-square value of the current at the centre. If we take away one-half of the antenna, some other conductor having capacity has to be substituted for it, and this must have a capacity at least equal to that of the remainder of the oscillator. We may therefore employ some sheet of metal laid on or near the ground, even insulated from it, as the balancing capacity or counterpoise to the antenna itself. If the antenna has a very large capacity, as it must have for long-distance working, then the balancing capacity would become large also, and if put above ground would restrict access to the base of the antenna and be otherwise inconvenient. It is therefore in every way better to put it underground, in which case it becomes an earth plate.

The best form of balancing capacity in any case is a series of copper wires radiating outwards from the mast which carries the vertical antenna. These wires may be above ground and insulated.

They may lie on the ground or be buried in the ground as an earth plate. They should extend away from the foot of the antenna for a distance at least equal to its height and be of good conducting metal. Some addition to the damping is without doubt introduced by the earth connection, but there are ways of compensating for it; for although connection to earth may increase the decrement of an oscillator, the decrement can also be decreased by the addition of inductance and capacity to it. Hence we may compensate for one by the other. In numerous cases the use of a balancing capacity perfectly insulated from the earth is impracticable. When an earth plate is employed certain precautions should be taken in making it. It is desirable in the first place to have it in two separate portions, so that the resistance to earth can be measured by measuring the resistance between the two earth plates. This cannot be done when the plate is in one piece. Also, if possible, provision should be made for wetting the earth plate and for examining it periodically to see if corrosion has set in.

The form of this plate is important. It is found that long narrow strips give less earth-plate resistance than a single square or round strip.

The general theory of earth-plate resistance is as follows: Let a conductor of any form be supposed to be buried in an infinitely extended medium of resistivity, ρ. Then suppose the conductor buried in the medium to be charged to a potential V, and to have a charge Q. The quotient $\frac{Q}{V}$ is the capacity (C) of the body. Let I be the current proceeding normally from unit area of the conductor into the medium. Let E be the normal electric force, and dn an element of length of the normal, and dS an element of surface of the conductor. Then—

$$-\frac{dV}{dn} = E \qquad \text{and} \int E\,dS = 4\pi Q$$

$$\text{also} \quad \frac{dV}{dn}dn = \frac{\rho\,dn}{dS}I\,dS = E\,dn \text{ by Ohm's law}$$

$$\text{Hence} \quad \rho\int I\,dS = \int E\,dS = 4\pi Q$$

$$\text{or} \quad \frac{4\pi Q}{\rho V} = \frac{\int I\,dS}{V} = K = \text{conductance of the dielectric}$$

$$\text{Therefore} \quad \frac{4\pi}{\rho}C = K$$

$$\text{and} \quad \frac{1}{K} = R = \frac{\rho}{4\pi C} \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (97)$$

Hence the total resistance of the buried conductor is numerically equal to the quotient of the resistivity of the surrounding earth by the capacity of the body in homologous units. Hence for any given position that form of earth plate will give the least earth resistance which has the largest capacity.

In making an "earth" we are concerned with initial cost and durability. The cheapest form of earth plate consists of a number of stout, stranded, thickly galvanized iron wires, or, better, bare stranded

copper wires spreading out radial-fashion like the roots of a tree underground. In that manner we obtain the greatest earth-plate capacity. Strips of zinc plate are also often used. In this case, however, care must be taken not to solder a copper wire to the zinc if the joint is buried underground, or else the plate at the joint will be destroyed by galvanic action.

Apart altogether from the insulation or non-insulation of the antenna from the earth, whether conductively connected to it or connected through a condenser, or, on the other hand, united to an insulated balancing capacity, the nature of the earth's surface, whether sea or land, damp or dry soil, between the sending and receiving stations, exercises a great effect upon the range of radiotelegraphy possible with any given apparatus. We must, therefore, consider the function of the earth generally in this matter.

It has already been shown in Chap. II. that high frequency alternating currents or oscillations are chiefly confined to the surface of the conductors conveying them. The penetration of the current into the conductor is less, the greater the conductivity and the greater the magnetic permeability of the material of which it is made.

This can be illustrated by an experiment shown by the author in a discourse at the Royal Institution on June 4, 1909, as follows :—

An oscillatory circuit is constructed, consisting of a condenser comprising one or more Leyden jars, a rectangular wire circuit having a gap in it which can be bridged, and a spark gap. The gap can be closed by inserting in it a short wire spiral, consisting of a copper, iron, or brass wire about No. 14 S.W.G. gauge, and each of the same length, viz. 30 to 40 cms. wound up in short open spirals of 8 or 10 turns. Oscillations are set up in this circuit by an inductive coil as usual. Alongside of this circuit is placed a cymometer with Neon tube as indicator, the brightness of the glow serving as an index of the amplitude and damping of the oscillations in the primary circuit. If then the spirals are successively placed in the primary circuit, and the cymometer circuit adjusted to resonance, we may place the cymometer so near the primary that when the copper or brass spiral is in circuit the Neon tube glows brightly, but when the iron spiral is in circuit the tube hardly glows at all. If then a galvanized iron wire of the same thickness and length is substituted, it will be found that the tube glows as brightly as when the copper spiral is employed. This shows that the thin layer of zinc put on the iron is sufficient to prevent penetration of the oscillations into the iron ; in other words, that they are confined to the surface.

If, however, we paint the iron spiral or even cover it with a thick layer of badly conducting plaster of Paris, it still damps the oscillations as much as a bare iron wire, showing that the oscillations penetrate through the badly conducting layer of plaster or paint. We have already, in Chap. II. § 1, given the fundamental equations for the current established in a conductor, viz.—

$$\frac{4\pi\mu}{\rho}\frac{du}{dt} = \frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + \frac{d^2u}{dz^2} \quad . \quad . \quad . \quad . \quad . \quad (98)$$

and two similar equations in v and w, when u, v, and w are the rectangular components of the current and μ and ρ are the permeability and resistivity of the conductor.

The meaning of this equation will best be understood by applying it to a particular case. Let us suppose a plane surface to separate a conductor of conductivity $\frac{1}{\rho}$ and permeability μ from a dielectric of unit permeability and zero conductivity. Let x be the direction of an axis measured from any point in the plane perpendicular to the surface, whilst the y and z axes lie in that plane. If then a current is established in the conductor, it will begin at the surface and diffuse inwards by a process resembling the conduction of heat. If the current is alternating, it may be represented by the real part of the function $U\epsilon^{jpt}$. Hence, since there is no variation in the direction of y and z, the equation (98) reduces to

$$\frac{4\pi\mu p}{\rho} ju = \frac{d^2u}{dx^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (99)$$

and if a^2 denotes $\frac{4\pi\mu pj}{\rho}$, we have—

$$\frac{d^2u}{dx^2} = a^2u \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (100)$$

as the equation expressing the current diffusion into the conductor.

The solution of this is

$$u = A\epsilon^{-ax} + B\epsilon^{ax} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (101)$$

and since $u = 0$, when $x = \infty$, the constant $B = 0$, or $u = A\epsilon^{-ax}$

$$\text{Now} \quad (1 + j)^2 = 2j \qquad \text{when } j = \sqrt{-1}$$

$$\text{Hence} \quad a = \sqrt{\frac{2\pi\mu p}{\rho}}(1 + j) \quad . \quad . \quad . \quad . \quad . \quad . \quad (102)$$

$$\text{And} \quad u = U\epsilon^{-\sqrt{\frac{2\pi\mu p}{\rho}}x}\epsilon^{j\left(pt - \sqrt{\frac{2\pi\mu p}{\rho}}x\right)} \quad . \quad . \quad . \quad (103)$$

Accordingly, the current u decreases in amplitude and changes in phase as we penetrate into the conductor. The current is reduced to $\frac{1}{\epsilon}$ of its value at the surface at a depth equal to $\frac{\sqrt{\rho}}{\sqrt{2\pi\mu p}}$

Thus, for instance, if the conductor is copper we have $\mu = 1$, $\rho = 1600$, and if the frequency of the alternations is 10^6, then—

$$\sqrt{\frac{2\pi\mu p}{\rho}} = 2\pi\sqrt{\frac{n}{\rho}} = 157$$

The current therefore is reduced to $\frac{1}{\epsilon} = 0{\cdot}367$ of its amplitude or strength at the surface at a depth of $\frac{1}{157}$ of a centimetre, or about $\frac{1}{400}$ of an inch.

It can be shown that the resistance of the conductor in a direction

parallel to the surface to alternating currents of a frequency n is the same as that of strips of thickness $\frac{1}{2\pi}\sqrt{\frac{\rho}{\mu n}}$ to steady currents. Hence, in the above case a strip or sheet about $\frac{1}{16}$ of a mm. or $\frac{1}{400}$ of an inch thick would present the same resistance to steady currents as does the slab of infinite thickness to currents of a frequency of 1 mm. flowing parallel to the bounding surface. If then we consider a strip of metal of finite thickness and ask the question, For what limiting frequency has the strip practically the same resistance for alternating as for steady currents? it is easy to see that the upper limit of the frequency n is given by solving the equation—

$$\frac{1}{\pi}\sqrt{\frac{\rho}{\mu n}} = t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (104)$$

where t is the given thickness. Thus, for oscillations of frequency 10^6, if a strip of copper has a thickness not exceeding $\frac{1}{25}\pi$ cm. or about $\frac{1}{8}$ mm., it will have the same resistance as for steady currents. In other words, its high frequency resistance will be the same as its ohmic resistance.

The same principles are applicable in the passage of an electric wave over a conducting surface. The wave is an alternation of electric force perpendicular to, and magnetic force parallel to the surface. The magnetic force diffuses into the surface and there dissipates energy as heat which is drawn from that of the wave. Hence the operations taking place when an ordinary low frequency current is established in a conductor and when an electric wave moves over its surface are identical in this respect that the conductor absorbs and dissipates energy.

This penetration depends, as we have seen, upon the conductivity of the surface over which the wave glides.

If the surface is a very good conductor, the wave penetrates into it very little, but glides over the surface. If it is a poor conductor, the wave penetrates into it to a greater extent, and the worse the conductivity the deeper the penetration.

The materials of which the earth's crust is composed, with some exceptions, owe their electric conductivity chiefly to the presence of water in them. They are called electrolytic conductors. Substances like marble and slate when free from iron oxide are fairly good insulators. Dry sand or hard dry rocks are poor conductors, but wet sand and moist earth are fairly good conductors. Sea water, owing to the salt in it, is a much better conductor than fresh water. The following table gives some figures, which however are only approximate, for the specific resistance of various terrestrial materials in ohms per metre cube. It will be seen that dry sand or soils are of very high specific resistance, and damp or wet sand or clay fairly low.

TABLE I.—APPROXIMATE CONDUCTIVITY AND DIELECTRIC CONSTANT OF VARIOUS TERRESTRIAL MATERIALS.

Material.	Specific resistance in ohms per metre cube.	Dielectric constant. Air = 1.
Sea water	1	80
Fresh water	100 to 1000	80
Moist earth	10 to 1000	5 to 15
Dry earth	10,000 and upwards	2 to 6
Wet sand	1 to 1000	9
Dry river sand	very large	2 to 3
Wet clay	10 to 100	—
Dry clay	10,000 and upwards	2 to 5
Slate	10,000 to 100,000	—
Marble	5,000,000	6
Mercury	0·000001	infinity

If our earth's surface had a conductivity equal say to that of copper, then the electric radiation from an antenna would glide over the surface without penetration. In the case of the actual earth there is, however, considerable penetration of the wave into the surface, and therefore absorption of energy by it.

We are in the habit of speaking of electric or Hertzian wave telegraphy as "wireless" telegraphy, regardless of the fact that some of the functions of the wire in ordinary conductive telegraphy are taken by the earth in case of radiotelegraphy.

In the older method the wire serves as a guide to the energy, but at the same time, so to speak, charges a commission for this service in the shape of the energy dissipated in it as heat. In the latter case the earth's surface acts to some extent as the guide, and it also takes toll for that office by dissipating some of the wave energy. Electromagnetic waves of long wave-length, generated at the transmitting station, thus lose energy as they travel over the earth's surface by penetration into and absorption by the terrestrial surface. It has long been known that radiotelegraphy is conducted with greater ease over sea than over land, but the reasons for this difference were not at once apparent. An important contribution was, however, furnished by a theoretical investigation made by Dr. J. Zenneck, in a paper entitled "The Propagation of Plane Electromagnetic Waves over a Plane Conducting Surface with Reference to Wireless Telegraphy." [40]

Dr. Zenneck considers the case of a plane electric wave travelling without divergence over a surface bounding two media of different conductivity and dielectric constant. It is obviously desirable to simplify the problem by leaving out of account at first the diminution of wave amplitude by mere distance, and also that due to curvature of the bounding surface. Let the direction of propagation be taken

[40] See J. Zenneck, "Über die Fortpflanzung ebener elektromagnetischer Wellen längs einer ebenen Leiterfläche und ihre Beziehung zur drahtlosen Telegraphie," *Annalen der Physik*, vol. 23, p. 846, 1907.

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as that of the x axis, whilst the direction of the z axis is downwards into the denser medium or soil, and the direction of the y axis is away from the reader (see Fig. 57). This convention as to axes may be called the German system, as opposed to the English, in which the direction of the z axis would be upwards. The German system has the advantage that it correctly represents the relation between the electric and magnetic forces in the wave and the direction of propagation. For in this case if x is the direction of wave propagation, then y is the direction of the magnetic force, and z that of the electric force of the wave, these vectors being in the plane of the wave.

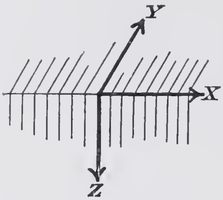


FIG. 57.

The following symbols will then be used:—Let K denote the dielectric constant of the medium in the C.G.S. system reckoned in electrostatic units, and let μ denote the magnetic permeability in electromagnetic units. Hence for air $K = 1$, $\mu = 1$. Then let s be the specific conductivity in electrostatic units, so that if ρ is the resistivity in ohms per centimetre cube, then $s = \dfrac{9 \times 10''}{\rho}$. Also let the frequency be denoted by n and $2\pi n$ by p. Let $u = 3 \times 10^{10}$ be the wave-velocity, λ the wave-length, and $2\pi\lambda = q$. We shall employ the letter j to denote $\sqrt{-1}$. Hence the expression for any vector is in the form $a + jb$.

Let the axial components of the electric force E be denoted by X, Y, and Z, and those of the magnetic force H by α, β, and γ.

Consider, then, a small rectangular element of volume taken in the medium close to the bounding surface, and with one corner at the origin (see Fig. 58). Let the side parallel to the x axis have a length δx, that parallel to the z axis have a length δz, and that parallel to the y axis a length unity. Then through the surfaces of this volume the electric and magnetic forces create displacement D and magnetic flux F per unit of area. If K is the dielectric constant of the material, then $D = \dfrac{KE}{4\pi}$, or, writing k for $\dfrac{K}{4\pi}$, we have $D = kE$; also $F = \mu H$, where μ is magnetic permeability. These fluxes and forces are connected in accordance with the two circuital laws of electro-magnetism as follows:—

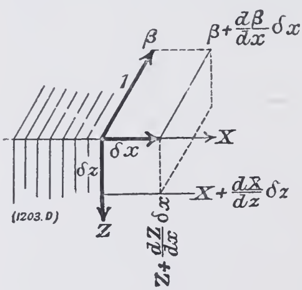


FIG. 58.

(i.) The line integral of magnetic force round the boundary of a curve taken in the dielectric is numerically equal to 4π times the total electric currents through that area.

(ii.) The line integral of electric force round any area is numerically equal to the time rate of decrease of magnetic flux through that area.

Let us apply the above theorems to the sides of the small element of volume. If s is the conductivity in electrostatic units of the

material and $k = \frac{K}{4\pi}$, then for the side $1 \times \delta x$ normal to the z axis, the electric force Z produces through it a conduction current $sZ\delta x$ and also an electric displacement $kZ\delta x$, and therefore a displacement current $pkZ\delta x$, which is in quadrature as regards phase with the conduction current. Hence the total current is $(s + jpk)Z\delta x$.

To reduce this current to electro-magnetic units we must divide by $u = 3 \times 10^{10}$, and, therefore—

$$\frac{4\pi}{u}(s + jpk)\,Z\delta x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (105)$$

is equal by the first law to the line integral of the magnetic force round the area $1 \times \delta x$. This latter is equal to

$$\beta - \left(\beta + \frac{d\beta}{dx}\delta x\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (106)$$

Since the magnetic force is wholly in the plane of the wave, and therefore β is the only component concerned. Accordingly we have—

$$\frac{4\pi}{u}(s + jpk)\,Z = -\frac{d\beta}{dx} \quad . \quad . \quad . \quad . \quad . \quad . \quad (107)$$

Now the electric and magnetic forces in an electric wave are pulsating vectors which we shall assume are simple harmonic functions of the space and time. Therefore, mathematically we can take the components of the electric and magnetic forces as proportional to the real part of $\epsilon^{j(pt + qx)}$, because this function is equal to $\cos(pt + qx) + j\sin(pt + qx)$ and $\cos(pt + qx)$ represents a wave motion, since it is a function which is periodic, both with regard to x and t, or space and time. Accordingly, if $\beta = A\epsilon^{j(pt + qx)}$, then $\frac{d\beta}{dx} = jq\beta$, and we have—

$$\frac{4\pi}{u}\left(s + jpk\right)Z = -jq\beta \quad . \quad . \quad . \quad . \quad . \quad . \quad (108)$$

In the same way, if we take the total current through the area $1 \times dz$, and parallel to the x axis, we obtain the equation—

$$\frac{4\pi}{u}\left(s + jpk\right)X = \frac{d\beta}{dz} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (109)$$

In the next place apply the second law to the area $\delta x\delta z$.

The line integral of electric force round this area is—

$$Z\delta z - \left(Z + \frac{dZ}{dx}\delta x\right)\delta z - X\delta x + \left(X + \frac{dX}{dz}\delta z\right)\delta x = \left(\frac{dX}{dz} - jqZ\right)\delta x\delta z \quad (110)$$

The time rate of change of the magnetic flux through this area is $\mu\beta\delta x\delta z$.

Hence we have—

$$u\left(\frac{dX}{dz} - jqZ\right) = jp\mu\beta\,;$$

or dividing both sides by 4π and putting μ' for $\frac{\mu}{4\pi}$, we have—

$$\frac{dX}{dz} - jqZ = \frac{4\pi}{u}jp\mu'\beta \quad . \quad . \quad . \quad . \quad . \quad . \quad (111)$$

If we write v for $\frac{u}{4\pi}$ our equations take the form—

$$(s + jpk)Z = -vjq\beta \quad . \quad . \quad . \quad . \quad . \quad . \quad (112)$$

$$(s + jpk)X = v\frac{d\beta}{dz} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (113)$$

$$\frac{dX}{dz} - jqZ = \frac{1}{v}jp\mu'\beta \quad . \quad . \quad . \quad . \quad . \quad . \quad (114)$$

Eliminating X and Z from the above equations, we have—

$$\frac{d^2\beta}{dz^2} = \left\{q^2 + j\frac{p\mu'(s + jpk)}{v^2}\right\}\beta \quad . \quad . \quad . \quad . \quad (115)$$

The solution of (115) is $\beta = \epsilon^{-jBz}$, where—

$$B^2 = -\left\{q^2 + \frac{jp\mu'(s + jpk)}{v^2}\right\}$$

or

$$B^2 + q^2 = -j\frac{p\mu'(s + jpk)}{v^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (116)$$

Hence, since β varies as $\epsilon^{j(pt + qx)}$, we have for the complete expression—

$$\beta = A\epsilon^{-jBz}\,\epsilon^{j(pt + qx)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (117)$$

where A is some constant.

From (112), (113), and (114) we then easily find that—

$$X = -jBA\frac{v}{s + jpk}\epsilon^{-jBz}\,\epsilon^{j(pt + qx)} \quad . \quad . \quad . \quad (118)$$

$$Z = -jqA\frac{v}{s + jpk}\epsilon^{-jBz}\,\epsilon^{j(pt + qx)} \quad . \quad . \quad . \quad . \quad (119)$$

Suppose then that we apply these equations and solutions to two small solid rectangles of side-lengths δx, 1, and δz taken in the direction of the axes, but one taken in the dielectric below the bounding surface and one in the air above (see Fig. 59).

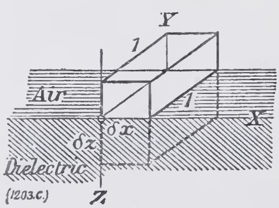


Fig. 59.

In the air the equations take the form—

$$\left.\begin{aligned}(s + jpk)\,Z &= -vjq\beta \\ (s + jpk)X &= -v\frac{d\beta}{dz} \\ \frac{dX}{dz} - jqZ &= \frac{1}{v}jp\mu'\beta\end{aligned}\right\} \quad . \quad (120)$$

In the dielectric as above—

$$\left.\begin{aligned}(s' + jpk)\,Z' &= -vjq\beta' \\ (s' + jpk)\,X' &= v\frac{d\beta'}{dz} \\ \frac{dX'}{dz} - jqZ' &= \frac{1}{v}\,jp\mu'\beta'\end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (121)$$

where the accents denote quantities in the dielectric. The solutions are—

$$\left.\begin{aligned} \beta &= \mathrm{A}\epsilon^{-j\mathrm{B}z}\ \epsilon^{j(pt+qx)} \\ \mathrm{X} &= -j\mathrm{BA}\frac{v}{s+jpk}\epsilon^{-j\mathrm{B}z}\ \epsilon^{j(pt+qx)} \\ \mathrm{Z} &= -jq\mathrm{A}\frac{v}{s+jpk}\epsilon^{-j\mathrm{B}z}\ \epsilon^{j(pt+qx)} \end{aligned}\right\} \quad . \quad . \quad (122)$$

$$\left.\begin{aligned} \beta' &= \mathrm{A}'\epsilon^{-j\mathrm{B}'z}\ \epsilon^{j(pt+qx)} \\ \mathrm{X}' &= j\mathrm{B}'\mathrm{A}'\frac{v}{s'+jpk'}\epsilon^{-j\mathrm{B}'z}\ \epsilon^{j(pt+qx)} \\ \mathrm{Z}' &= -jq\mathrm{A}'\frac{v}{s'+jpk'}\epsilon^{-j\mathrm{B}'z}\ \epsilon^{j(pt+qx)} \end{aligned}\right\} \quad . \quad . \quad (123)$$

Then, as shown above, the values of B and B′ are given by the equations—

$$\left.\begin{aligned} \mathrm{B}^2 + q^2 &= -jp\mu'\frac{s+jpk}{v^2} \\ \mathrm{B}'^2 + q^2 &= -jp\mu'\frac{s'+jpk'}{v^2} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (124)$$

At the bounding surface the horizontal components of the magnetic force—viz. β and β'—are identical. We have, then, when we put x, z, and $t = 0$ in the above equations (123) and (124), $\mathrm{A} = \mathrm{A}'$. Again, since $\mathrm{X} = \mathrm{X}'$ when x, z, and $t = 0$, we have—

$$\frac{\mathrm{B}'}{s'+jpk'} = -\frac{\mathrm{B}}{s+jpk}$$

For brevity let us write T for $s + jpk$, and T′ for $s' + jpk'$, and also P for $\frac{p\mu'}{v^2}$.

Then the above relations may be written—

$$\left.\begin{aligned} \mathrm{B}^2 + q^2 &= -jp\mathrm{T} \\ \mathrm{B}'^2 + q^2 &= -jp\mathrm{T}' \\ \frac{\mathrm{B}}{\mathrm{T}} + \frac{\mathrm{B}'}{\mathrm{T}'} &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (125)$$

Hence—

$$\mathrm{B}^2 + jp\mathrm{T} = \mathrm{B}'^2 + jp\mathrm{T}'$$

and

$$\left.\begin{aligned} \mathrm{B}^2 &= -j\mathrm{P}\frac{\mathrm{T}^2}{\mathrm{T}+\mathrm{T}'} \\ \mathrm{B}'^2 &= -j\mathrm{P}\frac{\mathrm{T}'^2}{\mathrm{T}+\mathrm{T}'} \\ q^2 &= -j\mathrm{P}\frac{\mathrm{TT}'}{\mathrm{T}+\mathrm{T}'} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (126)$$

Also we have from equation (122)—

$$\frac{X}{Z} = \frac{B}{q} = \sqrt{\frac{T}{T'}} = \sqrt{\frac{s + jpk}{s' + jpk'}} \quad . \quad . \quad . \quad . \quad (127)$$

In the case of air we may consider the conductivity zero. Accordingly—

$$\frac{X}{Z} = \sqrt{\frac{jpk}{s' + jpk'}} = \sqrt{\frac{j\dfrac{pk}{s'}}{1 + j\dfrac{pk'}{s'}}}$$

Let m stand for $\frac{pk}{s'}$ and m' for $\frac{pk'}{s'}$. Then—

$$\frac{X}{Z} = \sqrt{\frac{jm}{1 + jm'}}$$

Suppose 2ϕ is an angle whose tangent is $\frac{1}{m'}$, then we have by a well-known theorem—

$$\epsilon^{j2\phi} = \cos 2\phi + j \sin 2\phi$$

or

$$\epsilon^{j2\phi} = \frac{m'}{\sqrt{1 + m'^2}} + j\frac{1}{\sqrt{1 + m'^2}} = \frac{j + m'}{\sqrt{1 + m'^2}}$$

or

$$\epsilon^{j2\phi} = \sqrt{1 + m'^2}\, \frac{j(1 - jm')}{(1 - jm')(1 + jm')}$$

$$= \frac{j}{1 + jm'} \sqrt{1 + m'^2}$$

Therefore—

$$\frac{X}{Z} = \sqrt{\frac{jm}{1 + jm'}} = \sqrt{\frac{m}{\sqrt{1 + m'^2}}} \cdot \epsilon^{j\phi} \quad . \quad . \quad . \quad (128)$$

Accordingly, X and Z are two vectors which differ in phase by an angle ϕ such than $\tan 2\phi = \frac{s'}{pk'}$.

We are now prepared to apply these formulæ to numerical calculations. It must be remembered that k stands for $\frac{K}{4\pi}$, where K is the dielectric constant as usually measured. Also s stands for the conductivity in electrostatic units, and is therefore equal to $\frac{9 \times 10^{20}}{r \times 10^{9}}$, where r is the specific resistance in ohms per centimetre cube. Accordingly—

$$\tan 2\phi = \frac{1}{m'} = \frac{4\pi \times 9 \times 10^{20}}{2\pi n K r \times 10^{9}} = \frac{18 \times 10^{11}}{nKr}$$

Suppose, then, that we select a wave length of 1000 feet or 300 metres as our radiotelegraphic wave, and consider the wave to be

travelling in air and over the surface of sea water for which $K = 80$ and $r = 100$. Then $n = 10^6$, and we have $\frac{1}{m'} = 225$, or $2\phi = 90^\circ$ and $\phi = 45^\circ$. Also $m = \frac{1}{18{,}000}$.

Hence—

$$\sqrt{\frac{m}{\sqrt{1 + m'^2}}} = \frac{1}{134} \quad . \quad . \quad . \quad . \quad . \quad . \quad (129)$$

This shows, therefore, that when waves 1000 feet in length travel over sea water the horizontal component X of the electric force in the air is negligible, since

$$\frac{X}{Z} = \frac{1}{135}\epsilon^{j\frac{\pi}{4}}$$

Therefore the electric force at the sea surface is nearly perpendicular to that surface, and is a nearly pure alternating force. The same applies to the magnetic vector.

Suppose in the next place that electric waves of the same length are being propagated over very dry land. In this case we should have $K = 2$ and $r = 10^6$ nearly. Hence, if $n = 10^6$ we have—

$$\tan 2\phi = \frac{1}{m'} \frac{18 \times 10^{11}}{2 \times 10^{12}} = 0{\cdot}9$$

or—

$$2\phi = 42^\circ \text{ or } \phi = 21^\circ \text{ (nearly)}$$

Also $\frac{1}{m} = 1{\cdot}8$. Hence—

$$\sqrt{\frac{m}{\sqrt{1 + m'^2}}} = 0{\cdot}625 \text{ (nearly)}$$

In this case, therefore, the horizontal component X of the electric force in the air is $62\frac{1}{2}$ per cent. of the vertical component in magnitude, and they differ in phase by 21°.

When two vectors differ in phase and size they compound into a pulsating vector represented by the rotating radius vector of an ellipse.

The electric vector in the wave travelling over dry land is therefore not by any means perpendicular to the surface, but is inclined to it, and there is a considerable rotating component. The resultant electric force in the air above the ground may be represented by the rotating radius vector of an ellipse, the major axis of which is inclined forward in the direction in which the wave is travelling (see Fig. 60).

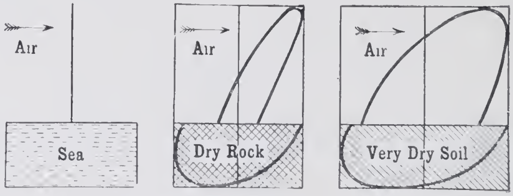
We have to consider, in the next place, the loss in amplitude or intensity of the wave as it travels along due to the absorption of energy by the surface over which the waves are travelling.

The amplitude of either wave vector is expressed by a function of the form $M\epsilon^{j(pt + qx)}$.

If we call the amplitude at the origin M_0, then $M_0 = M\epsilon^{jpt}$. At

a certain distance x' along the x axis the amplitude will have fallen to $\frac{1}{\epsilon}$ of that at the origin; we then have—

$$M\epsilon^{-1}\epsilon^{jpt} = M\epsilon^{j(pt + qx')} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (130)$$



$r = 1$ ohm/metre cube. K = 80. (*a*) $r = 100{,}000$ ohms/metre cube. K = 2–3. (*b*) $r = 10{,}000$ ohms/metre cube. K = 1–3. (*c*)

r = Resistivity. K = Dielectric constant.

FIG. 60.

Now q is a complex quantity; let it be written in the form—

$$q = a + jb$$

Then—

$$qx' = jax' - bx'$$

Therefore we have—

$$\epsilon^{-1}\epsilon^{jpt} = \epsilon^{-bx'}\epsilon^{j(pt + ax')}$$

Hence—

$$bx' = 1$$

or

$$x' = \frac{1}{b}$$

Accordingly, if we can express the value of q in the form $q = a + jb$, then we see that $\frac{1}{b}$ is the distance in which the amplitude decays to $\frac{1}{\epsilon}$ of that at the origin by reason of the absorption of energy by the surface over which the waves travel. We have, therefore, to express the value of q in the form $a + jb$. Dr. Zenneck has shown how this may be done as follows:—

Referring to equations (126) we see that

$$q^2 = -jP\frac{TT'}{T + T'}$$

where—

$$P = \frac{p\mu'}{v^2}$$

$$T = s + jpk, \text{ and } T' = s' + jpk'$$

If the waves travel in air, then we may put $s = 0$, and we have—

$$q^2 = \frac{p^2\mu'k}{v^2} \; \frac{s' + jpk'}{s' + jp(k + k')} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (131)$$

The following theorem will then be found useful.

If $a + jb$ is any vector, and if $\tan \phi = \frac{b}{a}$, then it is clear that—

$$\sqrt{a^2 + b^2}\, \epsilon^{j\phi} = a + jb$$

This follows at once from the known exponential values of $\sin \phi$ and $\cos \phi$, and the geometrical signification of $a + jb$.

Accordingly, we may write the expressions $s + jpk$ in the form

$$\sqrt{s^2 + p^2k^2}\, \epsilon^{j\phi}$$

where

$$\tan \phi = \frac{pk}{s}$$

Therefore, from (131) we have—

$$q = \sqrt{\frac{p^2\mu' k}{v^2}} \sqrt{\frac{\sqrt{s'^2 + p^2k'^2}}{\sqrt{s'^2 + p^2(k + k')^2}}}\, \epsilon^{j\left(\frac{\phi_1 - \phi_2}{2}\right)} \quad . \quad . \quad (132)$$

where

$$\tan \phi_1 = \frac{pk'}{s'}$$

and

$$\tan \phi_2 = \frac{p(k + k')}{s'}$$

Let $\sqrt{s'^2 + p^2k'^2}$ be represented by the letter R, and $\sqrt{s'^2 + p^2(k+k')^2}$ by R^1; then, remembering that $v = \frac{(3 \times 10^{10})}{4\pi}$, and $k = \frac{K}{4\pi}$, and $\mu' = \frac{\mu}{4\pi}$, where $K = 1$ and $\mu = 1$ for air, we have—

$$a + jb = q = \frac{p}{3 \times 10^{10}} \sqrt{\frac{R}{R'}} \left\{ \cos \frac{\phi_1 - \phi_2}{2} + j \sin \frac{\phi_1 - \phi_2}{2} \right\}$$

Hence—

$$b = \frac{p}{3 \times 10^{10}} \sqrt{\frac{R}{R'}} \sin \frac{\phi_1 - \phi_2}{2} \quad . \quad . \quad . \quad . \quad (133)$$

where

$$\tan \phi_1 = \frac{pk'}{s'} \text{ and } \tan \phi_2 = \frac{p(k + k')}{s'}$$

Accordingly, the value of $\frac{1}{b}$, or the horizontal distance at which the wave amplitude falls to $\frac{1}{\epsilon}$ of that at the origin, can be numerically calculated when the values of p_1, k', and s' are given. In the case of air $k = \frac{1}{4\pi}$. Thus for very dry soil we might have values as follows: $s = 9 \times 10^{20} \times 10^{-16}$ $k' = \frac{2}{4\pi}$, and we may take p to be $2\pi \times 10^6$. It can then be shown from equation (133) that $\frac{1}{b} = 4$ kilometres.

In the above manner Dr. Zenneck has calculated the distances for diminution of amplitude to $\frac{1}{\epsilon}$ for terrestrial surface materials of various conductivities and dielectric constants, and for an assumed wave-length of 300 metres, corresponding to a frequency of 10^6, and set out the results in curves reproduced in Fig. 61.

It is, then, at once seen that there is a certain soil conductivity which produces the maximum loss of amplitude for a given distance. It is clear that this should be the case, for if the terrestrial surface were a perfect conductor the waves would not penetrate into it at all, whilst if it were a perfect non-conductor there would be penetration, but no dissipation of energy as heat.

From our equations other important deductions can easily be

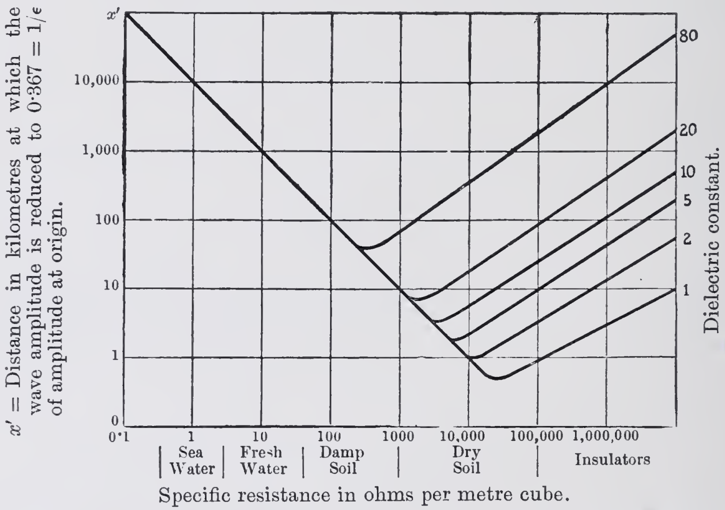


FIG. 61.—Curves showing Distance in which Electric Waves 1000 feet (300 Metres) in Length have their Amplitude reduced to $1/\epsilon$ by travelling over various Surfaces. (Dr. Zenneck.)

made as to the depth at which the amplitude of the waves penetrating into the earth is reduced to an assigned fraction, say $\frac{1}{\epsilon}$ of that at the surface. For if we refer to equations (123), it is seen that the magnetic force β' is a function of z the depth below the surface. Hence, if we put $z = 0$ we have—

$$\beta_0' = A'\epsilon^{j(pt+qx)}$$

where β_0' is the force at the surface.

Now, the exponent B is a complex quantity of the form—

$$-(c + jd)$$

and if z' is a certain depth at which the amplitude is $\frac{1}{\epsilon}$ of that at the surface, we have—

$$\beta' = \beta_0'\epsilon^{j(c+jd\ z'} = \beta_0'\epsilon^{jcz'}\epsilon^{-dz'}$$

If, then, $z' = \frac{1}{d}$ we have—

$$\beta' = \beta_o' \epsilon^{\frac{jc}{d}} \epsilon^{-1}$$

or $\frac{1}{d}$ is the depth at which the wave amplitude is reduced to $\frac{1}{\epsilon}$ of that at the surface.

Referring to equations (126), it is seen that—

$$B^2 = -jp \frac{T'^2}{T + T'}$$

and also that—

$$q^2 = -jp \frac{TT'}{T + T'}$$

Hence—

$$B = \sqrt{\frac{T'}{T}} \cdot q$$

But we have shown in equation (132) that q can be expressed in the form—

$$q = \frac{p}{V} \sqrt{\frac{\sqrt{s'^2 + p^2k'^2}}{\sqrt{s_1^2 + p^2(k + k')^2}}} \epsilon^{j\frac{\phi_1 - \phi_2}{2}}$$

It follows, then, that since $T' = s' + jpk'$ and $T = s + jpk$, that we have—

$$B = \frac{p}{V} \cdot \frac{\sqrt{s'^2 + p^2k'^2}}{\sqrt{\sqrt{s^2 + p^2k^2}\sqrt{s'^2 + p^2(k + k')^2}}} \epsilon^{j\left(\phi_1 - \frac{\phi_2}{2} - \frac{\phi}{2}\right)} \quad (134)$$

where

$$\tan \phi_1 = \frac{pk'}{s'}, \ \tan \phi_2 = \frac{p(k + k')}{s'}$$

and

$$\tan \phi = \frac{pk}{s}$$

Now we know that—

$$\epsilon^{j\left(\phi_1 - \frac{\phi_2}{2} - \frac{\phi}{2}\right)} = \cos\left(\phi_1 - \frac{\phi_2}{2} - \frac{\phi}{2}\right) + j \sin\left(\phi_1 - \frac{\phi_2}{2} - \frac{\phi}{2}\right)$$

and if $B = c + jd$, then equating real and unreal parts, and remembering that $s = 0$ for air, we find for the value of d the expression

$$d = \frac{\sqrt{p}}{3 \times 10^{10}} \frac{\sqrt{s'^2 + p^2k'^2}}{\sqrt{k}\sqrt{\sqrt{s^{12} + p^2(k + k')}}} \sin\left(\phi_1 - \frac{\phi_2}{2} - \frac{\phi}{2}\right) \quad . \quad (135)$$

and $\frac{1}{d}$ gives us the depth at which the wave amplitude is reduced to $\frac{1}{\epsilon}$ of that at the surface.

The expressions (133) and (135) are of great practical utility.

For example, let us suppose electric waves having a wave length

of 300 metres or 1000 feet, are travelling over sea-water. The question is, how far does this wave penetrate into the water before its amplitude is reduced to $\frac{1}{\epsilon}$ of that at the surface?

The air has a dielectric constant $K = 1$ and a conductivity zero. The sea-water has a resistivity of 100 ohms per centimetre cube. Hence for air

$$k = \frac{1}{4\pi} \text{ and } s = 0$$

for sea-water

$$k' = \frac{80}{4\pi} \text{ and } s' = \frac{9 \times 10^{20}}{10^{11}}$$

Also

$$p = 2\pi \times 10^6 \qquad u = 3 \times 10^{10}$$

Therefore

$$\tan \phi = \frac{pk}{s} = \propto \quad \therefore = 90^0$$

and

$$\tan \phi_1 = \frac{pk'}{s'} = \frac{4}{900} \quad \therefore \phi_1 = 0^0$$

and

$$\tan \phi_2 = \frac{p(k + k')}{s'} = \frac{4}{900} \quad \therefore \phi_2 = 0^0$$

Accordingly

$$d = \frac{\sqrt{2\pi \times 10^6}}{3 \times 10^{10}} \sqrt{\frac{(81 \times 10^{18} + 1600 \times 10^{12})12{\cdot}5}{\sqrt{81 \times 10^{18} + 1640 \times 10^{12}}}} \frac{1}{\sqrt{2}}$$

which is very nearly to $\frac{1}{50}$. Hence, $\frac{1}{d} = 50$ cms., or the amplitude of the wave would be reduced to 0·367 of the amplitude at the surface at a depth of ½ metre. Hence, below a depth of 4 or 5 metres there could be no amplitude at all. In other words, when such waves travel over sea-water their effect is wholly confined to a surface layer a few feet in thickness.

If, however, we consider the propagation to take place over very dry soil, for which the conductivity in electrostatic units might be as small as $9 \times \frac{10^{20}}{10^{16}}$, we should find that the value of the distance $\frac{1}{d}$ might then amount even to 100 metres or more, showing that the penetration of the wave into soil of small conductivity and small dielectric constant is very considerable. Dr. Zenneck set out the results of calculations for various cases in a series of curves as given in Fig. 62.

The conclusions to which the above investigation leads are that in the case of radiotelegraphy the nature of the earth's surface material between the sending and receiving stations must exercise a very important influence on the wave energy captured by a given

receiving antenna at a given distance; and that the transmission is effected with the least loss over sea. This is entirely in accordance with experience. Again, the results show that the effect of dry soil in reducing the wave amplitude is as much due to its small dielectric constant as to its small conductivity.

Dr. Hack has shown in another paper that underground water or moisture, not on the surface layer, is of assistance in reducing the loss of wave amplitude.[41]

A matter of great practical importance is the consideration of the effect of wave length on the dissipation of wave energy by soil absorption. If, for instance, we propagate over sea and land electric waves 1000 feet, and also of 10,000 feet in wave length, what difference in the loss of wave amplitude by soil absorption will be produced?

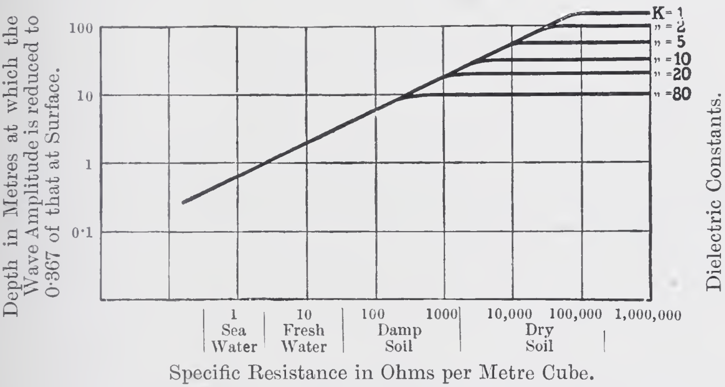


Fig. 62.—Depth of Penetration of Waves 1000 Feet in Length. (Dr. Zenneck.)

This question can be answered by the help of equation (133). We will consider the case of transmission (1) over sea; (2) over moist land; (3) over very dry land.

1. *Transmission over Sea.*—The resistivity of sea-water may be roughly taken as 100 ohms per centimetre cube. Hence, $s' = 9 \times 10^9$ electrostatic units. The dielectric constant of sea-water $= K = 80$; therefore $k' = \frac{80}{4\pi}$. The dielectric constant of air $= 1$; therefore $k = \frac{1}{4\pi}$.

We shall take the case of waves 300 metres and 3000 metres long.

(*a*) $\lambda = 300$ metres, $n = 10^6$, $p = 2\pi \times 10^6$, $pk' = 40 \times 10^6$, $p(k + k') = 40{\cdot}5 \times 10^6$, $\tan \phi_1 = \frac{pk'}{s'} = 0{\cdot}00444$, $\tan \phi_2 = \frac{p(k + k')}{s'} = 0{\cdot}00445$.

Therefore

$$\sin \frac{\phi_1 - \phi_2}{2} = \tfrac{1}{2}\, 10^{-5}$$

[41] See F. Hack, "Die Ausbreitung ebener elektromagnetischer Wellen langs eines geschichteten Leiters, besonders un der Fällen der drahtlosen Telegraphie," *Annalen der Physik.*, vol. 27, p. 43, 1908.

Now, $s'^2 + p^2k'^2$ is nearly equal to $s'^2 + p^2(k + k')^2$. Hence from (133)

$$b = \frac{2\pi \times 10^6}{3 \times 10^{10}} \cdot \frac{1}{2} \frac{1}{10^5} = \frac{1}{10^7} \text{ (nearly)}$$

or $\frac{1}{b} = 10{,}000$ kilometres.

(b) Suppose $\lambda = 3000$ metres, $n = 10^5$, $p = 2\pi \times 10^5$, $pk' = 4 \times 10^6$, $p(k + k') = 4{\cdot}05 \times 10^6$, $\tan \phi_1 = \frac{pk'}{s'} = 0{\cdot}000444$, $\tan \phi_2 = \frac{p'(k + k')}{s'} = 0{\cdot}000445$.
Therefore

$$\sin \frac{\phi_2 - \phi_1}{2} = \tfrac{1}{2}\, 10^{-6}$$

$$b = \frac{2\pi \times 10^5}{3 \times 10^{10}} \frac{1}{2} \frac{1}{10^6} = \frac{1}{10^{11}} \text{ (nearly)}$$

or $\frac{1}{b} = 1{,}000{,}000$ kilometres.

We see, therefore, that although a wave 300 metres long travels over sea-water with small absorption, the lengthening of the wave has yet a very beneficial influence in reducing the loss of amplitude.

2. *Transmission over Ordinary Land Surface.*—Since the degree of moisture, and therefore conductivity, of land surface soils differ very much, it is difficult to give a single number which can be taken as the value either of the conductivity or of the dielectric constant of dry land. We may, however, for the sake of an example, consider a case in which the specific resistance of the soil is 10,000 ohms per centimetre cube and the dielectric constant 5.

Then in this case we should have—

$$s' = 9 \times 10^7\ k' = \frac{5}{4\pi} \text{ and } k + k' = \frac{6}{4\pi}$$

If we take $\lambda = 300$ metres, then we have—

$$p = 2\pi \times 10^6\, pk' = \tfrac{5}{2} 10^6 p(k + k') = 3 \times 10^6$$

Hence

$$\frac{pk'}{s'} = \frac{5}{180} = 0{\cdot}028 = \tan 1^\circ\ 36'$$

and

$$\frac{p(k + k')}{s'} = \frac{6}{180} = 0{\cdot}033 = \tan 1^\circ\ 54'$$

Therefore

$$\sin \frac{\phi_1 - \phi_2}{2} = 0{\cdot}0026$$

$$b = \frac{2\pi \times 10^6}{3 \times 10^{10}} \times \frac{26}{10{,}000} = \frac{52}{10^8}$$

Since $s'^2 + p^2k'^2$ is so nearly equal to $s'^2 + p^2(k + k')^2$, and, therefore, $\frac{1}{b} = 20$ kilometres.

If, then, we take $\lambda = 3000$ metres, we find in the same manner $\frac{1}{b} = 2000$ kilometres. This shows clearly that lengthening the waves from 300 to 3000 kilometres greatly reduces the wave absorption over land.

3. However we take the case of an exceedingly dry surface soil having a resistivity of 10 megohms per centimetre cube, we should find that lengthening the waves from 300 to 3000 metres produced hardly any appreciable improvement in the loss of wave amplitude.

Accordingly we can draw the following conclusions as to the effect of wave length upon radiotelegraphic transmission.

1. In the case of transmission over sea, the absorption for waves of 300 metres long is not very large; but, nevertheless, increasing the wave length to 3000 metres is an advantage.

2. In transmission over land the absorption of waves 300 metres long is very sensible, and increasing the wave length to 3000 metres produces a very beneficial effect.

3. In the case of extremely dry soil the terrestrial absorption is very large, and increasing the wave length from 300 to 3000 metres produces no very marked improvement.

The final conclusion is that the superior transmission over sea is due to the relatively high conductivity and high dielectric constant of sea-water, and that in the case of transmission over land it is necessary to employ very long electric waves to obtain efficient transmission.

The subject has also been fully discussed by Brylinski (see *Science Abstracts*, vol. 10, A., p. 103, 1907, or *The Electrician*, vol. 57, p. 970, October, 1906).

Brylinski examines the general theory of the penetration of the wave into the soil when a plane wave passes over it with magnetic force parallel and electric force perpendicular to the surface. He takes the average resistivity of soil to be 66 ohms per metre cube, which is rather low, and that of sea-water to be 3·73, which is rather high. For a frequency of $\frac{10^7}{2\pi}$, he shows that the current or wave would penetrate into such soil about 50 metres, and that 95 per cent. of it would be within 6 metres of the surface. In the case of sea-water it would be about 0·25 metre.

Brylinski has considered the effect of the damping of the oscillations on the terrestrial absorption. He found that damping causes a somewhat complicated distribution of the current at various depths. In the upper layer the current density diminishes somewhat more rapidly than the undamped currents, and then at a certain depth more slowly.

Owing to the rapidity of decrease of current density with depth, the current is practically confined to a certain strip or layer, the resistance of which, in spite of the infinite extension of the soil downwards, is a perfectly definite quantity, which increases with the resistivity, frequency, and permeability of the soil and with the damping of the oscillations. Thus, for a soil of resistivity 66 ohms per metric cube, and a frequency of $\frac{10^7}{2\pi}$, the current density at a depth of 5 metres is only 21 per cent. of that at the surface, and at a depth of

10 metres only 4 per cent., and at 15 metres less than 1 per cent., assuming that undamped currents are employed. This implies that for such sort and frequency the penetration of the wave into it is practically confined to a depth of about 15 metres.

There is, therefore, no warrant for the conclusion that the earth exercises no particular influence over the passage of long electric waves over it, except by reason of obstacles and irregularities. On the contrary, it exercises a very important effect, and every change in moisture or shower of rain falling on its surface makes itself felt by a change in the facility for conducting radiotelegraphy over it. It is much to be desired that practical radiotelegraphists would, as far as possible, note these changes and collect material for further and fuller discussion of the question of the influence of the earth on radiotelegraphy.

15. Syntonic Wireless Telegraphy.—We have already made reference (see Chap. VII.) to the important practical problem of isolation in wireless telegraphy, and to methods of effecting it. We have also described the methods invented by Mr. Marconi for conducting syntonic radiotelegraphy, and the experiments of Lodge and Slaby. The problem is, to erect at some place a receiving appliance for electric wave wireless telegraphy which shall not be affected by any but the waves proceeding from certain assigned and correlated stations. The solution of this problem in its most complete form would involve three qualities in such a receiver.

(i.) It must not pick up or be affected by solitary waves or trains of electric waves sent by other transmitters than those with which it is intended to be in connection.

(ii.) It must be proof against nefarious attempts to hinder the reception of its proper communications.

(iii.) It must be free from disturbances or stray records due to atmospheric electric discharges or unintentional or natural electric waves.

The practical solutions so far given all depend upon the utilization of the principle of resonance between electric circuits.

These subdivisions of the problem have not all as yet been equally solved. The subproblem (i.) has been solved to a very large extent, and a receiver can be constructed which is limited in its range of reception to a particular and fairly well-defined small range of wave length, provided they are slightly damped.

It is impossible yet to define precisely the limits of affectation. The degree of "sharpness of the tuning," as it is technically termed, is to a large extent a question of skill on the part of the operator and the construction of the appliances. We have already shown, however, that receivers tuned for the reception of waves of such lengths as 300 to 2000 feet (commonly used in ship-to-ship and ship-to-shore communication) can be rendered quite immune from influence by the longer and more powerful waves sent out from power stations (see Chap. VII.). For certain forms of receiving apparatus, and when using undamped waves, even a change of $\frac{1}{2}$ or $\frac{1}{4}$ per cent. in the incident wave length is sufficient to prevent the adjusted receiver from responding.

The second subproblem concerned with violent interference has

received practical solution to a large extent by the legislation controlling wireless telegraphy in various countries, and such attempts to prevent communication have been rendered less important by being made illegal.

Any form of telegraphy, with wires or without, can be rendered impossible if an antagonist is permitted to employ sufficiently powerful means of disturbance in proximity to the station. The prevention of such interference is not more within the scope of the normal scientific problem of syntony than the measures to preserve peaceable citizens from assassination and assault come within the range of preventive medicine.

The third subproblem, viz. the annulment, partial or complete, of atmospheric disturbances, has also been to a considerable extent solved. These disturbances are very much a question of locality, and means which may be effective in temperate climates fail entirely during a thunderstorm in the tropics.

The difficulties which arise in connection with atmospheric electric discharges are related to electric wave wireless telegraphy very much in the same way as the disturbances which affect ordinary telegraphy with wires are related to earth currents and magnetic storms. There have been occasions during great magnetic storms, as in 1859, 1870, 1903, and 1909, when telegraphy by cable and wire was for a short time rendered perfectly impossible over wide areas. So in the tropics there are occasional thunderstorms and atmospheric states, which for the time being put an end to the possibility of conducting electric wave telegraphy, at least with high vertical antennæ.

We shall at present deal solely with the purely scientific problem of syntonic telegraphy. The conditions have to be ascertained under which a receiving arrangement of the type used for electric wave telegraphy becomes sensitive to a wider or narrower range of wave length. This involves the closer consideration of the problem of syntony.

Let us consider a sending antenna with total decrement Δ to act upon a receiving antenna at a distance, this last being inductively coupled to a closed oscillatory circuit containing the cymoscope. Let δ_1 and δ_2 be the decrements of the primary (antenna) and closed (cymoscope) circuits of the receiver respectively.

Moreover, let Δ be small compared with δ_1, that is, let the transmitter be feebly damped, and let δ_2 be small compared with δ_1, so that δ_1 is greater than Δ or δ_2, but δ_2 small compared with Δ. Then, if J_1 is the R.M.S. value of the current in the receiving antenna, and J_2 is that in the cymoscope or closed and inductively connected circuit containing the detector, and if J_1' and J_2' are the corresponding maximum values, when resonance is secured between the antenna and associated cymoscope circuit we have the following relation in virtue of equation (143) of Chap. III. :—

$$\frac{J_1'}{J_1} = \sqrt{1 + \frac{x^2\pi^2}{(\Delta + \delta_1)^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (136)$$

and since by supposition Δ is small compared with δ_1, this gives us—

$$\frac{J_1'}{J_1} = \sqrt{1 + \frac{x^2\pi^2}{\delta_1^{\,2}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (137)$$

In the above equations, x denotes $1 - \frac{n_2}{n_1}$ where n_1 is the frequency in the transmitter circuit, and n_2 is that in the receiver circuits, the ratio $\frac{n_2}{n_1}$ being nearly unity.

In the same way we have to consider the relation of the current in the secondary circuit of the receiver to the corresponding resonance current. It can be shown that in this case we have—

$$\frac{J_2'}{J_2} = \frac{J_1'}{J_1}\sqrt{1 + \frac{x^2\pi^2}{(\Delta + \delta_2)^2}} \quad . \quad . \quad . \quad . \quad (138)$$

or since δ_2 is small compared with Δ, this gives us—

$$\frac{J_2'}{J_2} = \frac{J_1'}{J_1}\sqrt{1 + \frac{x^2\pi^2}{\Delta^2}} \quad . \quad . \quad . \quad . \quad . \quad (139)$$

It is clear that the current in the secondary circuit of the receiver increases both with improved syntony between the primary and secondary circuits of the receiver, and with improved syntony between the transmitter and receiver antennæ.[42]

Obviously, then, from (137) and (139) we have—

$$\frac{J_2'}{J_2} = \sqrt{\left(1 + \frac{x^2\pi^2}{\Delta_2}\right)\left(1 + \frac{x^2\pi^2}{\delta_1^2}\right)} \quad . \quad . \quad . \quad . \quad (140)$$

Therefore the resonance current in the secondary circuit of the receiver is increased both by decreasing the damping of the closed or cymoscope circuit and by decreasing that of the transmitter.

Hence we have a confirmation of the well-known fact that a highly damped transmitter, such as a plain Marconi aerial or linear oscillator, cannot effect such sharp tuning or good syntonic telegraphy as a feebly damped transmitter of the inductively coupled type. This is verified by experience.

Suppose a resonance curve to be drawn for the secondary circuit of the receiver, we should find that the form of this curve would depend greatly upon the value of the transmitter decrement Δ. If the transmitter was feebly damped, then this resonance curve would be very peaked, and if the transmitter is strongly damped the curve would be rounded at the summit, as depicted in Fig. 63.

This implies that in the case of a feebly damped transmitter a small change in the oscillation frequency or time period of either receiver or transmitter greatly reduces the current in the receiving instrument; whereas in the case of a strongly damped transmitter this is not the case. The logical outcome of this is that if the transmitter is undamped, then extremely exact syntony is possible, and receivers can be constructed which will not respond except to waves of very precisely the same period as that for which they are tuned. For a fuller treatment of this subject, the reader is referred to a paper by M. Wien in the *Annalen der Physik*, 1902, 4th ser., vol. 8, p. 709.

[42] The above expressions, (137), (138), (139), (140), are identical with those given by Dr. J. Zenneck, in his book, "Elektromagnetische Schwingungen und Drahtlose Telegraphie," p. 892.

The general use of strongly damped transmitters is very disadvantageous, and the more their employment can be prevented the more perfect will radiotelegraphy become.

If a transmitter is used with large damping and great interval between the trains of waves, the R.M.S. value of the current in the transmitting antenna is very small compared with the maximum value of the current during a train.

This implies two things.

(i.) Such a transmitter necessarily must have an initial oscillation of large amplitude to be effective, and hence affects even non-syntonic receivers in its neighbourhood, because it is only by employing a large initial amplitude that we can obtain a sufficiently large R.M.S. value to be of use in the case of current-actuated cymoscopes.

(ii.) Considerable energy expenditure in charging the condenser or antenna to the necessary initial voltage to obtain the necessary maximum initial amplitude.

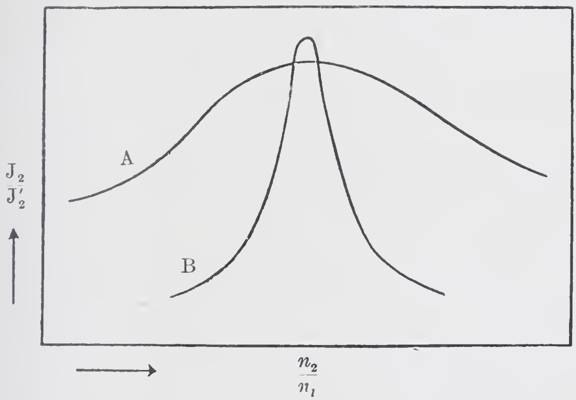


FIG. 63.—Graphical Representation of the General Forms of the Resonance Curves of an Inductively Coupled Receiver Circuit. A, when transmitter antenna is strongly damped; B, when transmitter antenna is feebly damped.

The receiver can only be made to respond, therefore, at a great distance by the use of a cymoscope, such as a coherer, which is chiefly affected by the maximum value in the train of waves operating on it. Hence such a receiver is more or less sensitive to other non-syntonic trains of sufficient amplitude, and is also sensitive to atmospheric electric disturbances. If, however, undamped waves are emitted by the transmitter, then a receiver of the bolometer type, or some cymoscope, only affected by the R.M.S. value of the incident wave, can be employed and rendered receptive, not by increased general sensitiveness, but by more exact syntony in the transmitting and receiving circuits.

The problem of practical wireless telegraphy has thus affinities with that of telephony. The telephone is very sensitive to induced currents. Hence a sensitive telephone receiver picks up all sorts of stray currents by induction, and the speaking is blurred. For practical long-distance work, what is required is not a more sensitive receiver, but a more powerful transmitter.

The stray disturbances are then drowned out by the proper currents, and the communication becomes good. So in the case of syntonic wireless telegraphy the elimination of disturbances is not to be achieved by the use of receivers of greater sensitiveness, but by employing transmitters producing prolonged trains of waves or with small damping, resulting in the possibility of sharper tuning.

The actuation of a syntonic receiver is due to a cumulative effect. Small electromotive forces applied at proper intervals end by producing a current or voltage of sufficient maximum or mean-square value to affect the particular cymoscope employed. Hence a receiver can be made insensitive to irregular or non-syntonic impulses, and yet sensitive to impulses of the right period. The question whether we have any advantage by increasing the frequency of the trains of oscillations or employing a continuous wave radiation is determined by the nature of the cymoscope or detector employed. If it is a potential actuated device such as a coherer, its operation is determined by the action on it of a certain minimum electromotive force, and provided the trains of waves sent out by the transmitter are long enough to create by cumulative effect the maximum electromotive force in the cymoscope circuit, we shall only employ energy wastefully at the transmitter station by crowding the trains of waves close together. It must be remembered that when a receiving antenna has oscillations set up in it by the impact of trains of waves it radiates, whilst at the same time it absorbs, and it is in the condition of a body which is being warmed by radiant heat. The temperature of such a body cannot rise higher than a limit fixed by its emissivity. Electrically speaking, good absorbers are good radiators, just as they are thermally. Hence an antenna must have a fairly large decrement if it is to be a useful receiver. This implies that it cannot accumulate oscillations indefinitely, and therefore cannot benefit to more than a certain extent by the impact on it of trains of perfectly continuous waves.

On the other hand, if we employ a cymoscope of the current actuated type, then since its indications are determined by the R.M.S. value of the oscillations in its circuit, we can benefit considerably by increasing the number of trains of waves per second or even making them continuous. But then, on the other hand, we have to consider the energy expenditure in the transmitting antenna. The power (P) given to the radiator varies as the total quantity of electric energy discharged per second across the spark gap, and therefore varies as the number of discharges (N) per second, and as the square of the charging potential (V^2).

This last varies as the square of the maximum current (I^2) in the antenna. Again, the mean-square current (J^2) in the antenna varies directly as (NI^2), and inversely as $n\delta$, where δ is the decrement and n the frequency of the oscillations. Hence we have—

$$P \propto NI^2 \propto n\delta J^2$$

If, therefore, we require a certain minimum value of J^2 in the sending antenna to affect the receiver at the other end, we can only do this, consistently with the avoidance of great power expenditure in the sending antenna, by obtaining a radiator with small decrement,

that is, one which sends out feebly damped or continuous trains of waves.

As regards the radiating antenna, the power expended on it would have to be enormously increased if we desired, and were able, to send out continuous trains of waves compared with that involved in sending out intermittent trains of waves of equal maximum value, but with decrement δ and identical frequency n, and at the rate of N trains per second. For the energy expenditure on the antenna is proportional to J^2 where J is the R.M.S. value of the current at the base of the antenna. If I is the maximum value of the current oscillations in each train, then (see Chap. III. § 2) we have—

$$J^2 = \frac{NI^2}{8n\delta}$$

Hence the power absorbed by the antenna when sending out the intermittent damped waves must be to the power absorbed in sending out continuous waves of equal maximum value, I, in the ratio of J^2 to I^2, or of $N : 8n\delta$. Suppose, then, that $N = 50$, $n = 10^6$, $\delta = 0{\cdot}2$, we should have $N : 8n\delta = 50 : 16 \times 10^5 = 1 : 32{,}000$. The power required to create a continuous train of waves would be 32,000 times greater than that required to create intermittent damped trains of the same maximum value.

Unless, therefore, the employment of continuous trains of waves results in the reduction to a very large extent of the necessary minimum R.M.S. value of the waves at the arriving station by the employment of a suitable syntonic detector, the advantages of improved syntonism might to a large extent be nullified by the enormously greater cost of manufacture of the continuous wave trains.

The fact that the production of continuous trains of waves involves great power absorption in comparison with the production of intermittent trains, is well seen in the case of the generation of powerful sound waves by steam or air syrens for coast warning purposes. As much as 600 horse-power has been found to be absorbed in the production of a continuous sound from a large air syren, whereas not a fraction of this would be required to make intermittent blasts at widely separated intervals of time. Returning then, to the consideration of the apparatus for syntonic electric wave telegraphy, the receiving arrangements consist of an antenna or receptive aerial, which is inductively or directly coupled to a closed oscillatory circuit, across which or in which the cymoscope is inserted. It is important that this closed circuit should have as small a coefficient of damping as possible.

In a non-radiative circuit without spark gap the damping factor is equal to $\frac{R'}{2L}$ where R' is the high frequency resistance and L the high frequency inductance. The damping factor determines the logarithmic decrement (δ) in the case considered, for then $\frac{R'}{2L} = 2n$. Accordingly, for a given frequency the damping factor is made small either by decreasing R' or increasing L. Theory, therefore, points out that in the closed cymoscope circuit the resistance should be kept as small as possible, and the inductance made as large as

possible consistently with giving the circuit the necessary natural frequency.

Under these conditions the amplitude of the oscillations under electromotive impulses of syntonic frequency will accumulate or increase slowly, and hence the receiver circuit will only be affected by prolonged trains of waves of exactly the right frequency. Such a circuit may be called a *stiff* or *heavy* circuit, because it is analogous to a pendulum with a very heavy bob, which can be set in vibration

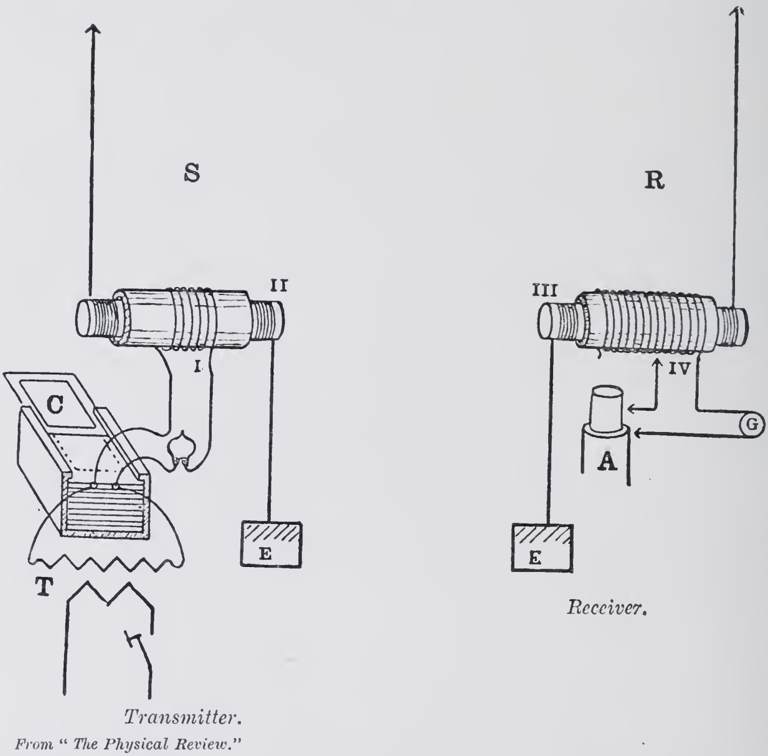


FIG. 64.—Apparatus for researches on Syntonic Electric Wave Telegraphy as used by Prof. Pierce. T, transformer; C, primary condenser; I, primary circuit of oscillation transformer; II, secondary circuit; E, earth plates; S, transmitting antenna; R, receiving antenna; III, IV, oscillation transformer in receiver; A, sliding condenser; G, cymoscope.

by very feeble blows, provided they come at the right intervals and are continuously repeated. Such a pendulum could be started into vigorous vibrations even by puffs of air, provided we puff exactly at the right time and keep on puffing, but it would hardly be moved at all by one single vigorous blow.

Various ways of connecting the cymoscope or wave detector to the closed oscillatory circuit of the receiver and this circuit, also to the antenna, have been described and illustrated in Chapter VII.

In order to reduce the high frequency resistance of the closed

oscillatory circuit of the receiver as much as possible, it should be made of fine silk-covered copper wire plaited into a flat band.

This stranding of the wire is especially important in the case of wires wound in spirals, as then the high frequency resistance is greater than the value circulated by the Rayleigh formula (see Chap. II. § 1).

In whatever way inventors may seek to disguise the construction of the syntonic receptive circuit by the introduction of condensers or of inductance coils, it invariably resolves itself into a closed circuit of as small a decrement as possible, inductively or directly connected with an absorbing antenna circuit of a fairly large decrement. The last decrement per half period will generally be about 0·2, and that of the closed circuit may with care be made as low as 0·002.

In confirmation of the above theory of syntonic telegraphy by electric waves, some excellently devised researches have been carried out by Professor G. W. Pierce.[43] For this purpose he employed inductively coupled antennæ. At a transmitting station a condenser circuit was established, consisting of a glass-plate primary condenser of variable capacity joined in series with the primary circuit of an oscillation transformer and with a Cooper-Hewitt discharger in place of a spark gap. The secondary circuit of the transformer was interposed between an aerial wire and an earth plate (see Fig. 64). At the receiving station he employed as detector a Fleming electrodynamometer, consisting of a disc of silvered paper suspended by a quartz fibre held in the interior of a coil (see Fig. 65).

The theory of this instrument has already been given (see Chap. II. § 13).

The silver disc carried a mirror, and its deflection, when oscillations passed through the coil, were read on a scale. This detector was connected in series with a variable tabular condenser and with the secondary circuit of an oscillation transformer, whose primary circuit was inserted between an earth plate and a receiving antenna. Observations were then made on the mean-square current as read by the electrodynamometer, with variations in the capacities and inductances in both sending and receiving circuits.

In one set of experiments the primary condenser capacity C_1 was varied step by step, and corresponding to each fixed value a set of current readings was taken with the secondary condenser capacity C_2 varied over a wide range.

It was found that for each value of C_1 a curve could be plotted of the secondary root-mean-square current J_2 in terms C_2. These curves all have a maximum value (see Fig. 66).

When all the curves were drawn, a family of curves presented itself, which showed that corresponding to any given value of C_1 there was a certain value of C_2 which gave the maximum antenna current.

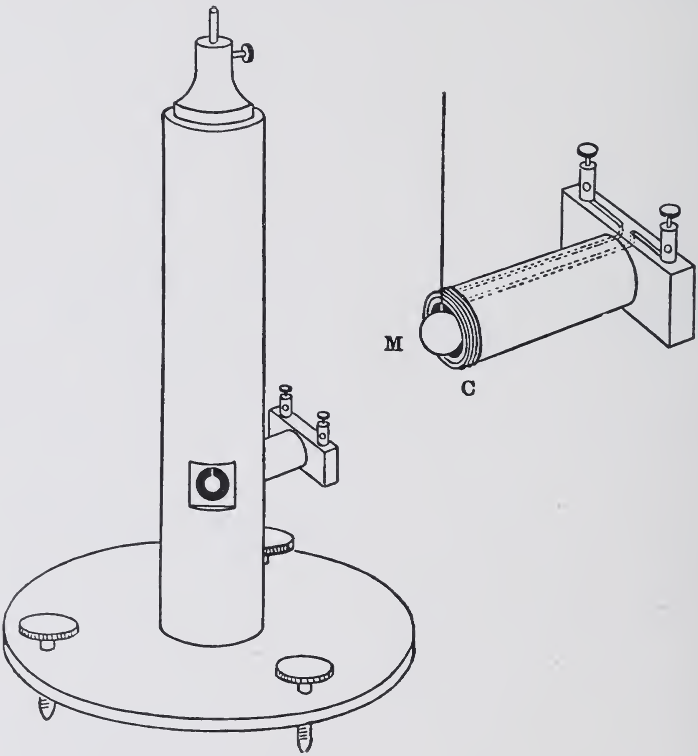
If an envelope is drawn to the whole family of resonance curves, it is seen to have principal and subsidiary maximum ordinates. This

[43] See *The Physical Reveiw*, September, 1904, vol. xix. p. 196; and April, 1905, vol. xx. p. 220, and vol. xxiv. p. 152, February, 1907, "Experiments on Resonance in Wireless Telegraph Circuits," by G. W. Pierce. The author is indebted to Prof. Pierce and the Editor of the *Physical Review* for kind permission to use the diagrams illustrating these papers.

indicates that there is some value of the secondary capacity which gives the largest antenna current, but also there is another value of that capacity which gives a secondary maximum. This is quite in accordance with theory as already given. The antenna current is determined by several factors.

(i.) It is increased by syntonizing the open and closed circuits of the transmitter.

(ii.) By syntonizing the open and closed circuits of the receiver.



From "The Physical Review."

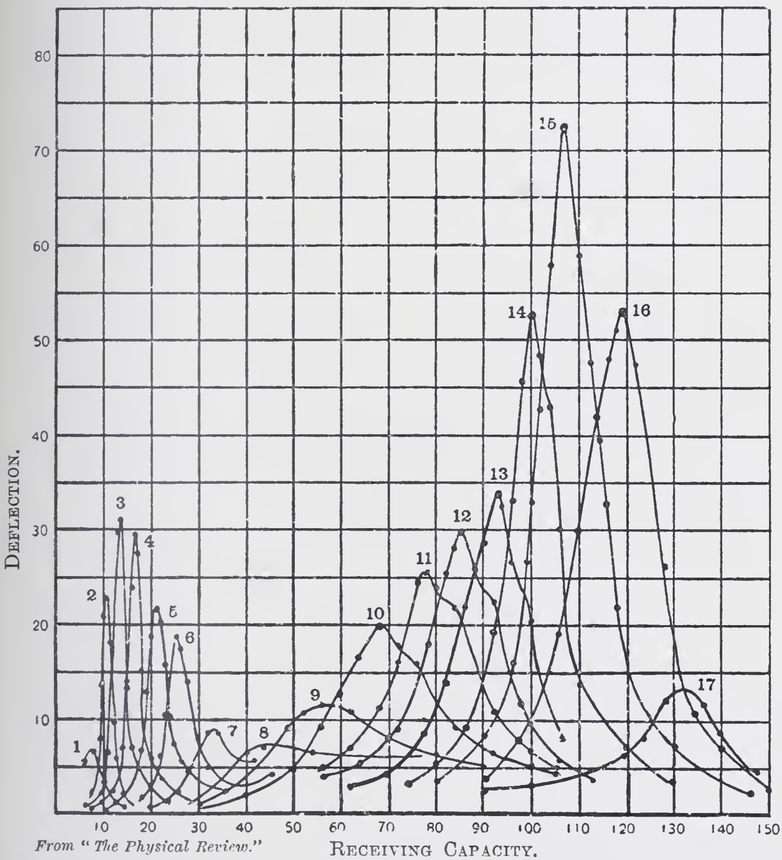
Fig. 65.—Form of Fleming Alternating Current Disc Galvanometer employed by Professor Pierce. M, disc of silvered paper suspended by quartz fibre: C, coil of wire through which oscillations are sent.

(iii.) By syntonizing the receiver as a whole to one or other of the two waves of different wave length sent out by the transmitter.

The above experiments bring out these facts well. There is a certain maximum value of the antenna current which occurs when the variation of secondary capacity finally syntonizes the two secondary circuits. There is a *maximum* maximum when the variation of primary capacity syntonizes the two circuits of the transmitter, and there is a subsidiary maximum according as the receiver is timed to one or other of the two frequencies set up in the transmitter antenna.

By photographing the oscillatory spark of the transmitter, Professor Pierce has been able to render visible the existence of these two frequencies in the condenser circuit, and by making wave length measurements of the radiated waves to show that the wave lengths of these are strictly in accordance with theory.

Referring to Chap. III. § 11, equations (66) and (67) for the time



From "The Physical Review."

FIG. 66.—A Family of Resonance Curves obtained by Professor Pierce, showing the Variation in the Galvanometer Deflection as the Capacity in the Sending and Receiving Circuits was varied.

periods T′ and T″ of the two oscillations in coupled oscillation circuits, it is easy to transform these into wave length equations by multiplying all through by the constant $3 \times 10^{10} = u$, and we then have—

$$L_1^2 = \frac{\lambda_1^2 + \lambda_2^2 + \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4k^2\lambda_1^2\lambda_2^2}}{2} \quad . \quad . \quad (141)$$

$$\text{and} \quad L_2^2 = \frac{\lambda_1^2 + \lambda_2^2 - \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4k^2\lambda_1^2\lambda_2^2}}{2} \quad . \quad . \quad (142)$$

where L_1 and L_2 are the wave lengths of the two radiated waves when the circuits are coupled with a coefficient of coupling k, and λ_1 and λ_2 are the wave lengths proper to the primary and secondary circuits when far removed from each other and all other conductors.

We have already given in some detail an account of measurements made by Professor G. W. Pierce to put the above formulæ to test, and the confirmation he has given to them (see Chap. III. § 11; also see G. W. Pierce, "Experiments on Resonance in Wireless Telegraph Circuits," *The Physical Review*, vol. xxiv. p. 166, February, 1907).

Researches have also been conducted on syntonic telegraphy by Sir Oliver Lodge and Dr. Muirhead, which are described in the Paper entitled "Syntonic Wireless Telegraphy" (see *Proc. Roy. Soc. Lond.*, vol. 82, A., p. 227, 1909), to which we have already made reference. These experiments were made with Lodge-Muirhead radiotelegraphic apparatus, and had as their object to discover the influence of the form of the aerial and especially the influence of the earth connection upon syntonic telegraphy. After enunciating the general principles upon which syntonic telegraphy depends, the authors describe their own arrangements for producing trains of oscillations in the sending antenna, each consisting of thirty to forty oscillations. The antenna was completely insulated, consisting of upper and lower capacity areas with a multiple spark gap in the centre. The antenna was charged by a high-voltage transformer, the secondary terminals of which were connected to the outer members of the half-dozen balls with five gaps forming the spark gap.

The radiating antenna was, therefore, essentially a Hertzian oscillator set with its axis perpendicular to the earth's surface. No actual measurements of the damping appear to have been made, but the spark was photographed to ascertain the number of oscillations in a train. At the receiving end a similar antenna was employed with a Duddell thermal ammeter as wave detector. The receiving antenna was put more or less out of tune with the incident waves by varying an inductance in series with it. Resonance curves were then drawn showing in arbitrary units the variation of the R.M.S. value of the current in the centre of the receiving antenna in terms of the inductance or wave length.

The chief result of these experiments is to show the dependence of the form of this resonance curve upon the height of the balancing capacity above the earth. On connecting the balancing capacity to the earth, or laying the lower area upon it, the resonance curve became quite rounded and ceased to exhibit any sharp maximum (see Fig. 67). The authors conclude, therefore, that the effect of the direct earth connection of the receiving antenna is always bad, and damps out the oscillations in it, thus hindering true syntonic telegraphy.

By raising the lower capacity to various heights above the ground it was found that there is for each station a best position or height of the lower area at which the station radiates most powerfully and receives best. The wave length employed in these experiments was about 440 metres, and the power employed at the sending end about

475 watts, the spark gap consisting of 5 gaps in series, each $\frac{3}{16}$ inch in length.

The record of the experiment does not show, however, whether the damping or decrement of the oscillations in the receiving antenna was increased by the earthing of the sending antenna.

These observations undoubtedly show that means are required for quickly and accurately measuring the decrement of the oscillations set up in the sending and in the receiving antenna without the laborious process of taking a resonance curve. Until this can be done we cannot conclude that in all cases the effect of the earth connection is to produce the same increase in the decrement as was clearly the case in the observations above described.

At present we may say that there are strongly opposed opinions

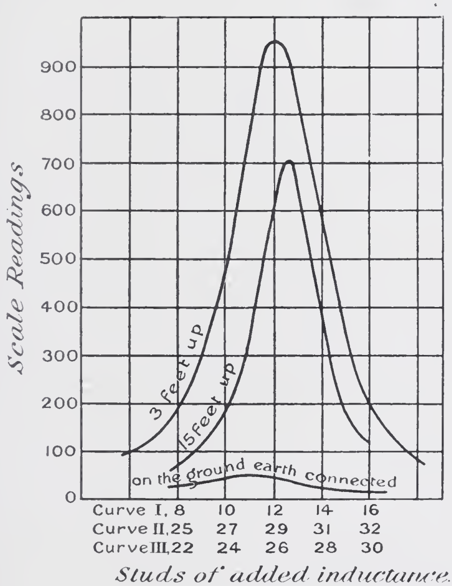


Fig. 67.

on the effect of the earth connection. Mr. Marconi and the majority of those who follow his methods use the earth connection at both sending and receiving ends, and consider that its advantages outweigh any objections to it, and in opposition to this Sir Oliver Lodge and his supporters consider that the earth connection is an evil and a serious obstacle to the conduct of effective syntonic telegraphy. The bulk of practical experience is, however, in favour of the earth connection, especially for long-distance working.

16. Dischargers for Spark Radiotelegraphy.—The physical process involved in the production of damped electric oscillations and corresponding electric wave generation consists in charging some form of condenser and then suddenly releasing the charge in the form of a spark, and permitting the free oscillations of the condenser to take place across the spark gap. When dealing with condensers

of small capacity charged with voltages of a few thousand volts, *e.g.* 20,000 or so, no particular difficulty occurs, all that is required is a spark gap, or series of spark gaps, consisting of a couple or more of metal balls of brass, zinc or iron, separated by intervals of a few millimetres which are inserted in series with the condenser and its inductive discharge circuit. The charging voltage is supplied by an induction-coil or small transformer, the secondary circuit of which is connected to the spark balls, or outer members of the series of balls.

As the potential difference of the balls increases the condenser becomes charged, and at a certain P.D. the limit of the dielectric strength of the air in the air gap for that particular gap length used is reached, and the air insulation breaks down. The spark gap at once becomes conductive and the circuit of the condenser is completed. It then oscillates until the energy of the charge is dissipated as heat and radiant wave energy.

The first point to notice in connection with this operation is that there may be a very large number of discharges of the condenser during one semiperiod of the transformer or during an interruption of the primary circuit of the induction coil.

This will happen when the spark gap is short. As the charging voltage and P.D. of the balls increase, a point is reached at which the air gap insulation breaks down and a train of oscillations ensues. If, however, the duration of this train is very short compared with one cycle of the charging voltage, then after this train of oscillation has subsided the P.D. of the balls increases again. Another spark and another set of oscillations will then take place, and this may be repeated three or four, or even many dozen, times during one semiperiod or cycle of the charging voltage. Hence it is quite erroneous to assume that there is only one spark per interruption of the primary of the coil or per semiperiod of the alternating current feeding the transformer. There may be a great many sparks in this time. This is called the phenomenon of multiple sparks. Moreover, these sparks do not occur at equidistant periods of time. They are generally very irregular. This is partly because the dielectric strength of the air in the spark gap is determined by the state of ionization in which it is left after the last discharge.

Another reason is the production of an electric arc or direct discharge of the transformer or induction coil across the gap, and until this is extinguished the condenser cannot again become charged. The actual discharge which occurs across the gap may be partly a true oscillatory condenser discharge, which we shall call the spark discharge, and partly a discharge of the nature of an electric arc taking place between the balls, which is due to current coming directly out of the induction coil or transformer, and not at all to the oscillatory discharge of the condenser. This arc discharge keeps down the potential difference of the balls, and it must be destroyed before the condenser can again become fully charged.

When employing large power transformers the production of an arc discharge has to be prevented by special means, and the object of design in large power dischargers is to prevent this arcing, and to cause the spark to be due entirely to electric energy coming out of the condenser and not at all to energy supplied directly by the

transformer. In short distance radiotelegraphic apparatus such as is provided on ships and small coast stations the usual source of voltage is a 10- or 12-inch spark induction coil. In these cases the discharger often takes the simple form of a pair of brass balls connected to the secondary terminals of the coil. There are the following objections to this rudimentary form of spark gap. The opposed surfaces of the balls become rough or worn away in time, the exact inter-distance or length of spark gap is not readily adjustable, the ionized air between the balls is removed irregularly by draughts, and lastly, but not least, the noise made by the spark is annoying and enables the signals being sent to be read by ear a long way off. In all cases, therefore, the spark balls should be enclosed in a more or less sound-proof chamber. This may be of cast-iron or very thick wood lined with asbestos. If the chamber contains air, then the spark will combine some of the nitrogen and oxygen into oxides of nitrogen, and ultimately with the aid of moisture these form nitric acid, which is deposited on the walls of the vessel. Hence the chamber must either contain some alkaline material, lime, potash, or soda, to absorb these vapours, or else fresh air must be continually passed through the chamber, or it must be made air-tight and filled with some gas, such as nitrogen, which is unaltered by the spark. Provision should also be made for easily altering the spark-gap length and for changing the opposed surfaces as they become eroded.

The author has found that this is most easily achieved by carrying the metal balls which form the discharge surfaces in a holder something like a ball castor used on the legs of tables. The ball is contained in a closely fitting tube, having a spiral spring behind it, and the tube has a screw ring on the end keeping the ball in place. The ball can then be turned round into various positions so as to expose clean surfaces when required.

Two such balls may be carried on the end of screwed rods having divided heads passing through metal bosses let into ebonite insulators, and these may be mounted so as to contain the balls in a stout box.

Another convenient form of discharger devised by the author consists of a pair of thick brass discs with rounded edges. These are carried on brass spring pedestals attached with a screw and nut so that the discs can be turned round to bring fresh places into opposition. The discs and pedestals are mounted so that the discs are on the same plane and their edges a few millimetres apart. The distance between the sparking points is then varied by means of two screws, which pass through the sides of a stout wooden containing box and press on the spring pedestals so as to force the discs nearer together. In all cases where the spark gap is contained in a silencing chamber it is convenient to have a peephole glazed.

A form of discharger for large spark discharges made by the Telefunken Company of Germany is shown in Fig. 68. It consists of two massive metal discs with round thickened flanges or tires, and one of these discs can be approached more or less to the other. The spark discharge takes place between the thickened edges of the two discs, which are insulated from each other, and continually changes its place of discharge.

In the case of dischargers for large power stations intended for

long distance radiotelegraphy, special difficulties have to be overcome in constructing a suitable discharger for heavy spark discharges. The chief difficulty encountered is the tendency of the transformer or transformers employed to charge the condensers to start an arc discharge at the same time, which, as already explained, reduces the potential difference of the balls, so that the condensers shunted across the discharger cannot again become charged until the arc is extinguished. Furthermore, with large discharge currents the metallic surfaces between which the discharge takes place become worn away very rapidly. This last difficulty is to a considerable extent mitigated by the employment of the rotating disc discharger devised by the author already described (see Chap. VII. § 16). In this case

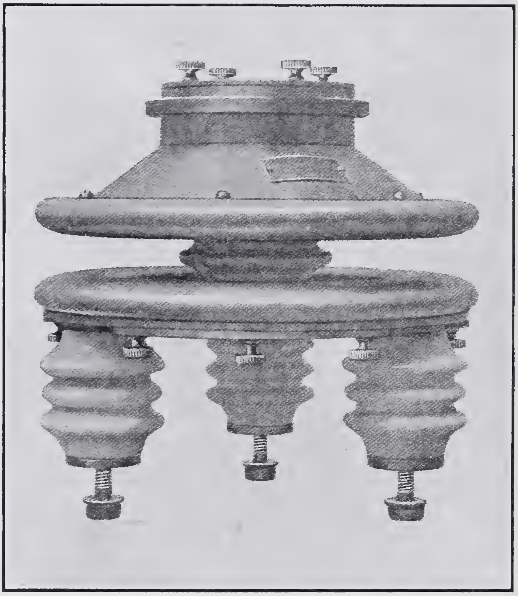


FIG. 68.—Telefunken Spark Discharger.

continually new and cool surfaces are presented between which the discharge takes place. The most convenient form for these surfaces is in the shape of two large cast-iron wheels with rounded edges, which are caused to rotate slowly and regularly by electric motors in the same direction. An air blast may also be employed to keep the surfaces between which a discharge takes place cool, so as to prevent volatilization of the metal and to some extent to limit the arc discharge.

In the design of dischargers for long-distance radiotelegraphic stations, Mr. Marconi made a very great advance in the years 1906–7 by the invention of his high speed rotating disc dischargers, which have greatly increased the speed of signalling possible in the case of large radiotelegraphic transmitters on the spark system,

and also have provided a means for producing practically continuous oscillations, or at least trains of electric oscillations very rapidly succeeding each other at extremely long intervals. The construction of these dischargers was described by the inventor himself in a lecture at the Royal Institution on March 13, 1908.[44] One form of the Marconi high-speed disc discharger is constructed as follows :—

A metal disc, A (see Fig. 69), insulated from the earth, is caused to rotate at very high speed, by means of a high-speed electric motor or steam turbine. The shaft which carries this disc passes through bearings in two pedestals, B, the upper parts of which, D, are insulated from the lower parts. These upper parts carry two other discs, C_1 and C_2, which may be called the polar discs, which can also be rotated at a very high speed. These polar discs have their edges placed very close to the surfaces or edges of the metal disc A. The

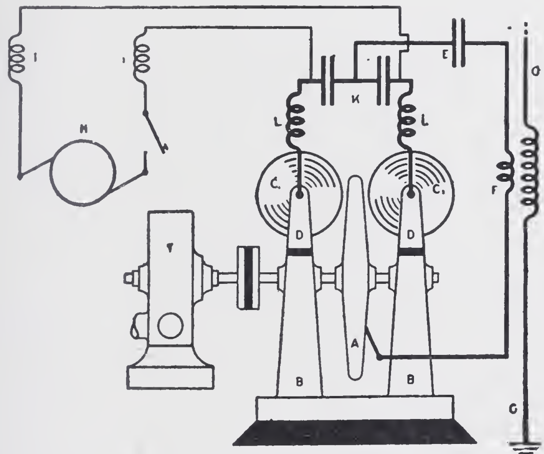


Fig. 69.—Marconi High Speed Rotating Disc Discharger.

two polar discs are connected respectively through suitable brushes or rubbing contacts to the outer ends or terminals of two condensers, K, joined in series, and these condensers are also connected through suitable inductive resistances, I, to the terminals of a high tension continuous current dynamo, H, although in some cases an alternator may be used instead. These condensers, K, will be referred to as the reservoir condensers. Against the central high speed or metal disc a suitable rubbing contact is provided, and connected between this contact and the middle point of the two condensers K is inserted an oscillatory circuit, consisting of a smaller condenser E in series with an inductance, which last is connected inductively or directly to the antenna. The circuit containing the condenser E and the primary coil F of the oscillation transformer is suitably tuned to the period of the antenna G. If the necessary conditions are fulfilled,

[44] G. Marconi, "On Transatlantic Wireless Telegraphy," *The Electrician*, vol. 60, p. 883, March, 1908. Also British Patent Specifications, G. Marconi, Nos. 8462, 1907; 8463, 1907; 20,119, 1907; also 8581 and 8582, both of 1909; and United States Patent No. 935,383, 1909.

and a sufficient electromotive force is employed when the dynamo H is put in action, and the discs caused to rotate, a discharge will take place between the outer discs and middle disc, which discharge is neither an oscillatory spark nor an ordinary arc, and powerful oscillations will be created in the signalling condenser E and the oscillatory circuit F.

Mr. Marconi states that in order to obtain good effects a peripheral speed of over 100 metres a second is desirable, and, therefore, particular precautions have to be taken in the construction of the discs both as to material and balancing. The inventor gives the following explanation of the operation of the discharger. He says: "Let us imagine that the source of electricity is gradually charging the double condenser K, and increasing the potential at the discs, say C_1 positively and C_2 negatively; at a certain instant the voltage will cause the charge to jump across one of the gaps, say between C_2 and A. This will charge the condenser E, which will then commence to oscillate, and the charge in swinging back will jump from A to C_1, which is charged to the opposite potential. The charge of E will again reverse, picking up energy at each reversal from the condensers K. The same process will go on indefinitely, the losses which occur in the oscillatory circuit EF being made good by the energy supplied from the generator H. If the disc is not rotated, or rotated slowly, an ordinary arc is at once established across the small gaps, and no oscillations take place. The efficient cooling of the discharge by the rapidly revolving disc seems to be one of the conditions necessary for the production of the phenomena."

If, therefore, a continuous current dynamo is employed, such a discharger, when properly adjusted, enables undamped oscillations to be obtained, the arc discharge being entirely suppressed, and replaced by a regular high frequency alternating current supplied from the condenser E. The principle, therefore, which underlies the working of the discharger is that to obtain an arc discharge between metal surfaces one of these surfaces, namely, the negative, must be allowed to become heated, and if it is permanently cooled, or kept below a certain temperature, true arc discharge is prevented; but at the same time this does not prevent a condenser discharge from taking place across the gap. The proof that the oscillations so produced are practically continuous is shown by the fact that Marconi found that the waves emitted from the sending antenna provided with such a discharger could not affect at a distance his magnetic detector, unless an interrupter was inserted in one of the circuits of the receiver.

Mr. Marconi has also devised another similar form of discharger with which he states the best results have been obtained over long distances, which provides a regular succession of feebly damped waves. This discharger consists of a disc, A, which can be rotated at a high speed (see Fig. 70), which carries upon its surfaces at regular intervals knobs or studs. These studs pass in the course of their revolution between two fixed or rotating discs, C_1, C_2, the rest of the electrical arrangements being, as already described in connection with Fig. 69. As this wheel rotates, each time the stud passes between the discs C_1, C_2 a discharge of the condenser E takes place; but any arc discharge which is formed is at once

extinguished, and on the passage of the next stud the condenser E is again able to furnish a train of oscillations. In this way an extremely regular series of slightly damped wave trains is produced which, when picked up at the receiving end by a suitable oscillation detector employed with a telephone, produce a clear musical note in the telephone which the ear can quite easily differentiate from the noises created by atmospheric electrical disturbances or other vagrant waves. These trains succeed each other at the rate of several hundred per second.

These high speed disc dischargers of Marconi have now stood the test of prolonged use, and proved of the greatest value in enabling long distance radiotelegraphic transmitting to be worked at a very high signalling speed and for long periods of time without inter-

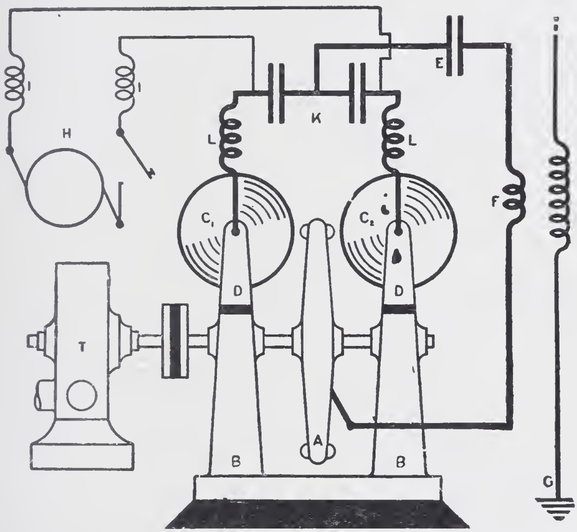


FIG. 70.—Marconi Studded Disc High-speed Rotating Discharger.

mission, both of which conditions are inseparable from success in commercial radiotelegraphy.

The theory of these Marconi dischargers has been investigated by Reinhold Rudenberg in an article entitled "Die Erwarmung rotierender Elektroden, insbesondere beim Marconischen Generator fur kontinierliche Schwingungen" (see *Jahrbuch der drahtlosen Telegrafie und Telephonie*, vol. ii. p. 18, 1908), to which the reader must be referred for details.

We have next to consider forms of discharger adapted for the method of excitation by shock (*Stosserregung*), the principles of which have already been explained (see § 11 of this chapter). It has already been shown that in a system of two coupled oscillation circuits, in one of which damped oscillations are excited by means of a spark gap, the reaction of the two circuits on one another produces in both of them oscillations of two frequencies. It has

also been mentioned that in the case of very short spark gaps the damping is extremely large, and that by availing ourselves of this fact it is possible to construct a transmitter producing damped waves in which the primary oscillation is damped out of existence after one or two oscillations, and the secondary is permitted to oscillate freely in a single period, and radiating therefore waves of a single wave length. Starting from Wien's researches on this matter, the Wireless Telegraph Company of Germany have devised forms of discharger for conducting spark telegraphy on this quenched spark system. In one form it consists of a series of copper discs or copper boxes with flat sides cooled with water, the outer surfaces of which are placed in contiguity, but separated by very thin rings of mica. The surface of the boxes or plates must be made extremely true and the interspace extremely small, about 0·15 or 0·1 of a millimetre, and ten or twelve of these discs or boxes may be placed in series. A groove is turned in the flat surface of the boxes, and the mica ring extends half-way across this groove, as shown in Fig. 71. This series of discs or boxes takes the place of the ordinary spark balls, and the outer members of the series are connected to the secondary terminals of a charging transformer fed by a high frequency alternator having a frequency of 800 to 1000 or more. The extremities of the series of discs or boxes are also connected to the oscillatory circuit consisting of a condenser in series with one coil of an oscillation transformer, the other coil in series with the antenna. When the charging transformer is in action it produces a very large number—1000 or more spark discharges in the discharger, which are quenched instantly, and these are accompanied by an equal number of condenser discharges, each of which is quickly damped. The directly or inductively coupled antenna hence receives a very large number of shocks or impulses per second, which set up its free vibrations. In Fig. 72 is shown a perspective view of this discharger as made by the Telefunken Company of Germany, taken from a description of their apparatus by Count Arco, given in a lecture delivered by him at Cologne in June, 1909 (see *The Electrician*, vol. 63, p. 461, July 2, 1909).[45]

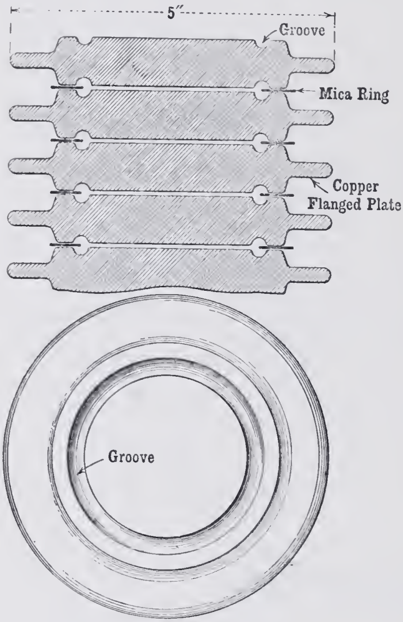
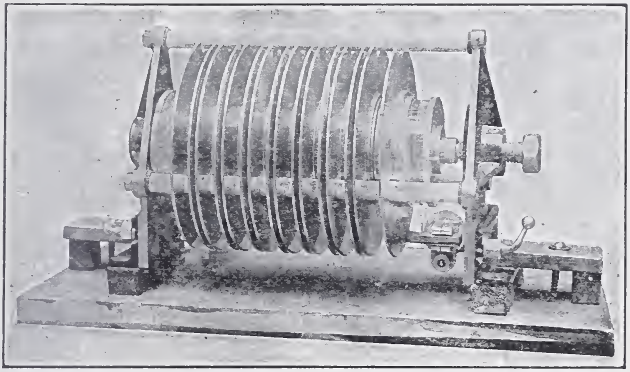


Fig. 71.—Quenched Spark Discharger.

To obtain efficiency and a quickly quenched spark, the opposed

[45] See British Patent Specification of W. P. Thompson, communicated by the Gesellschaft für Drahtlose Telegraphie, No. 6424 of 1909.

surfaces of this discharger must be made very smooth and perfectly plane and parallel, and are best made of silvered copper. The practical point of interest is, however, the time which they will remain smooth in practice. There is a tendency to become pitted, and the author has found that in this case the constancy and efficiency of the discharger fall off.



Taken by permission from "The Electrician."

FIG. 72.—Telefunken Quenched Spark Discharger.

A somewhat similar discharger composed of a pair of flat metal plates or concentric cones separated by a paper ring (see Fig. 73*a*) has been devised by Von Lepel.[46] These plates are connected to the

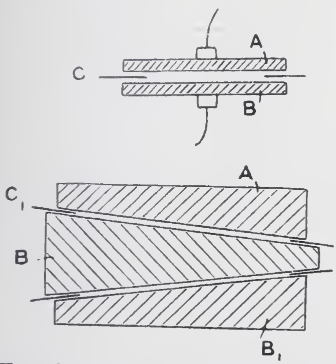


FIG. 73*a*.—Von Lepel Dischargers. A_1B_1 Metal Plates or Surfaces separated by a Paper Ring C or Rings C_1 C_2.

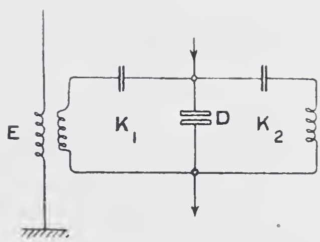


FIG. 73*b*.—Mode of Connection of the Von Lepel Discharger D to the Antenna E.

terminals of a high tension direct current dynamo, and are shunted by a pair of oscillatory circuits containing an inductance and capacity which are syntonized. The antenna is inductively or directly connected to one circuit (see Figs. 73*b* and 74).

The continuous voltage produces a series of intermittent quenched discharges between the plates, each of which is accompanied by a

[46] See British Patent Specification of E. von Lepel, No. 17,349 of 1908.

damped oscillation in the condenser circuits, and if an antenna is connected inductively or directly to one oscillatory circuit, free persistent slightly damped oscillations are set up in it.

Quite lately a third form of quenched spark discharger has been invented by Professor W. Peukert, of Brunswick, which makes use of a film of oil instead of a thin air gap as in the Telefunken or Von Lepel dischargers (see *The Electrician*, vol. 64, p. 550, January 14, 1910).

The Peukert discharger consists of a flat stationary metal disc, A,

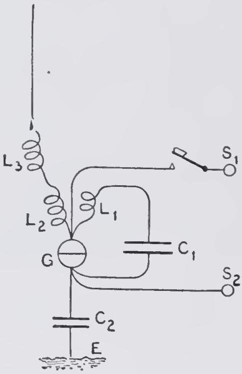


Fig. 74.—Connections of the Von Lepel Transmitter Circuits. G, Von Lepel Discharger; C_1 C_2, Condensers; L_1 L_2 L_3, Inductances; A, Antenna; S_1 S_2, Supply Terminals.

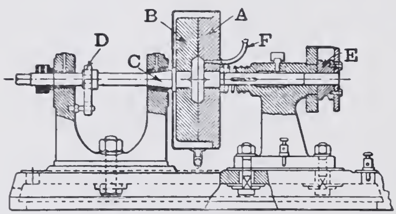


Fig. 75*a*.—Peukert Disc or Quenched Spark Discharger.

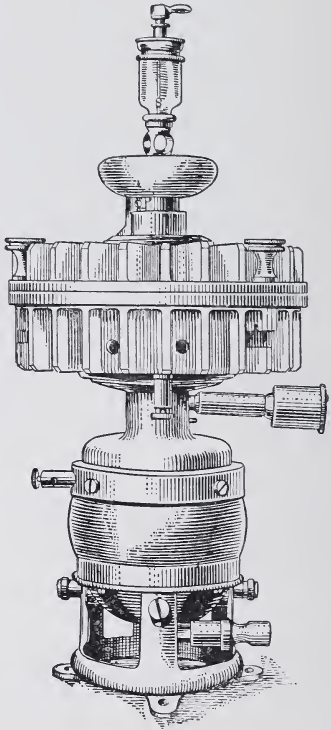


Fig. 75*b*.—Peukert Disc or Quenched Spark Discharger.

the face of which is kept flooded with oil through a small hole, F, in the disc (see Fig. 75*a*). Face to face with the fixed disc is another smooth metal disc, B, which can be made to revolve rapidly. The interspace between the discs is about 0·1 mm. The speed of the moving disc may be about 800 R.P.M. The discs are insulated from each other and form the two surfaces of the discharger. When a direct current voltage of about 200–400 volts is put on them the oil film is continually pierced, and if shunted by a condenser in series with an inductance rapidly damped oscillations are set up in this circuit.

For wireless work the discs are best placed in a horizontal position,

and one of them revolved by a small motor, and the discs may be flanged to keep them cool (see Fig. 75*b*). The discs are made of chemically pure copper, or copper plated with silver. Each gap or discharger must carry a current of not more than 4 amperes, but the voltage may be direct or alternating, and from 440 to 1500 volts.

Dischargers may, however, be arranged in series allowing, say, 800 volts for each gap. The discharger gives a perfectly quenched or damped discharge, so that if shunted by a condenser circuit inductively coupled to a second oscillating circuit, oscillations of only one frequency are set up in the latter although the coupling may be close.

The actual performance of any type of discharger can best be determined by the use of the author's photographic spark counter (see Chap. II. § 15), by which it is possible to determine at once how many sparks take place per alternation of the transformer, or per break of the induction coil primary, or per second. If the spark gap is very short a very large number of discharges of the condenser may take place at each interruption or alternate current period, as shown in the reproductions in Fig. 37, Chap. II., of spark photographs so taken.

It is, therefore, essential in any measurements of efficiency of the plant to apply the spark counter.

17. Condensers for Radiotelegraphic Stations.—It has been found by experience that only two dielectrics are suitable for employment in the construction of condensers for radiotelegraphic purposes. One of these is glass and the other air, either at ordinary pressures or in compression. If glass is employed, condensers may be built up of sheets of good crown glass with metal plates interposed. The best method of construction is to make the metal plates of thin sheet zinc which are cut out with a tool in the form shown in Fig. 76. These plates are built up with alternate sheets of glass, each cut an inch larger every way than the metal plates, the zinc plates being arranged with the lugs alternating, as shown in Fig. 62, Chap. I. The sheet zinc should not be too thin, so that when the whole mass of plates is immersed in oil in a stoneware or metal vessel, the oil penetrates in between the glass plates and excludes all air. The zinc plates on one side are connected together to a terminal and also those on the other. A sheet of crown glass 3 mm. or $\frac{1}{8}$ inch thick will bear safely an alternating voltage of 20,000 volts, equivalent to a 6 or 7 mm. spark. When higher voltages are employed such condenser boxes must be arranged in series. For any given dielectric there is a certain energy storage per cubic centimetre which cannot be exceeded, and in the case of glass this is equal to about 0·01 joule per cubic centimetre, or about 200 foot-pounds per cubic foot. Hence from this figure can be calculated the bulk of condenser glass required for a given energy storage or output of the condenser. The oil in which the condenser plates are immersed should be the highest insulation transformer oil and a thin paraffin oil or resinous oil is preferable to a thick vegetable

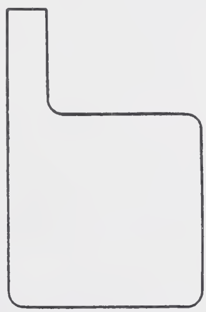


Fig. 76.

oil such as linseed oil. It is found, however, that glass plates employed as the dielectric in a condenser age with use and after a time punctures of the glass become more frequent. In Germany it is usual to employ condensers of the Moscicki type, consisting of large glass tubes closed at the bottom like large test-tubes a couple of metres long and a decimetre in diameter, the glass being blown so as to be thicker at the top than at the bottom. These tubes are then coated within and without with tinfoil to such a depth that at the edge of the tinfoil the glass is say half a centimetre in thickness, but below that only two or three millimetres. As already explained, this prevents puncture at the edges. Owing, however, to the ageing qualities of glass it has been found preferable in large stations to employ air condensers consisting of metal plates in air, either air at ordinary pressures with the plates separated to a considerable distance,

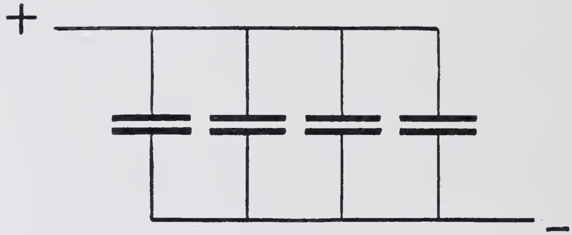


FIG. 77*a*.

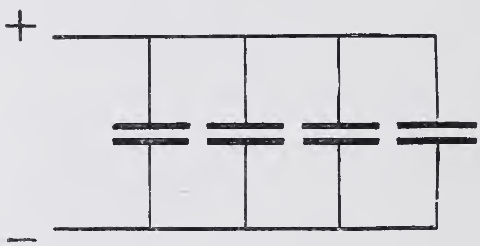


FIG. 77*b*.

Two Modes of Arranging Condensers in Parallel in a Discharge Circuit.

or else placed in a vessel with compressed air, which, therefore, has a much higher dielectric strength.

It remains to notice the manner in which these condensers should be connected to one another, and to the inductance and to the spark gap, in order to secure the best results. It is convenient to construct the primary condenser of a number of separate condensers, such as Leyden jars or glass-plate or micanite condensers, the elements being arranged either in series or in parallel, to give the capacity and dielectric strength required. If a number of condensers are to be arranged in parallel in series with the primary coil of the oscillation transformer and with a spark gap, then it is desirable that the length of the oscillatory path through its separate condenser should be the same. For this purpose condensers should be arranged as shown in Fig. 77*a*, and not as shown in Fig. 77*b*. In the first case the

length of the oscillatory circuit for each condenser is the same, in the second case it is different.

Where very high potentials are used, it is necessary to arrange condensers in series, or they may be partly arranged in series and partly in parallel, but the same conditions as to length of oscillatory path should be fulfilled. The connections between the condensers are best made with finely stranded cables made up of cotton-covered No. 36 S.W.G. copper wire twisted together. It is necessary to have sufficient surface for the discharge path and to avoid as much as possible introducing resistance into the primary circuit, so as to keep the decrement of the primary circuit as low as possible. In some cases it is necessary to charge condensers in series and discharge them in parallel, and this may be done in one of several ways shown in the appended diagrams (see Fig. 78).[47] In the appended diagrams, C_1, C_2 are the condensers, L_1 is the inductance coil, and S_1, S_2 are two spark gaps; I is an induction coil. It will be seen that the condensers are charged in series and discharged in parallel.

The best arrangement of condensers in the oscillation circuit of a wireless telegraph transmitter is determined by the following considerations. Let us assume that the antenna is inductively connected to the condenser or oscillation circuit. Then, in order that we may have syntony, we must make the oscillation constants of the two circuits the same. Let C_2 be the capacity of the antenna circuit and L_2 its inductance, so that $\sqrt{C_2L_2}$ is its oscillation constant. Let C_1 be the capacity of the condenser in the primary or nearly closed circuit and L_1 its inductance. Also let R_1 be the high frequency resistance of this circuit, including that of the spark gap. Then the oscillation constant is $\sqrt{C_1L_1}$ and the damping factor is $\frac{R_1}{2L}$. It has generally been the custom in spark telegraphy to make C_1 from ten to twenty times C_2, and hence L_2 must be from ten to twenty times L_1 in magnitude.

Accordingly, C_1 is a large capacity and L_1 is a small inductance. The resistance R_1 of the condenser circuit is largely made up of spark resistance. Hence for a given spark length the smaller we make L_1 the larger will become the damping and the greater the decrement of the oscillations.

It is advantageous, therefore, to keep the capacity C_1 as small as possible, so as to use as much inductance as possible in the condenser circuit. We can then only obtain the required energy storage by charging the condenser to a high voltage. This must, however, be achieved without increasing the length of spark gap, and can be accomplished by constructing the primary condenser of separate condensers which are charged in series, and each discharged across its own short spark gap, the several spark gaps being connected in series. The arrangements for effecting this are shown in Fig. 79, and are taken from a British Patent Specification, No. 20,804, of 1904, granted to the Wireless Telegraph Company of Berlin.

These diagrams show the mode of connecting the condensers and spark gaps in the case of inductively and directly coupled antennæ.

[47] See German patent granted to Fritz Lesemann, Class 21A, No. L. 18,521.

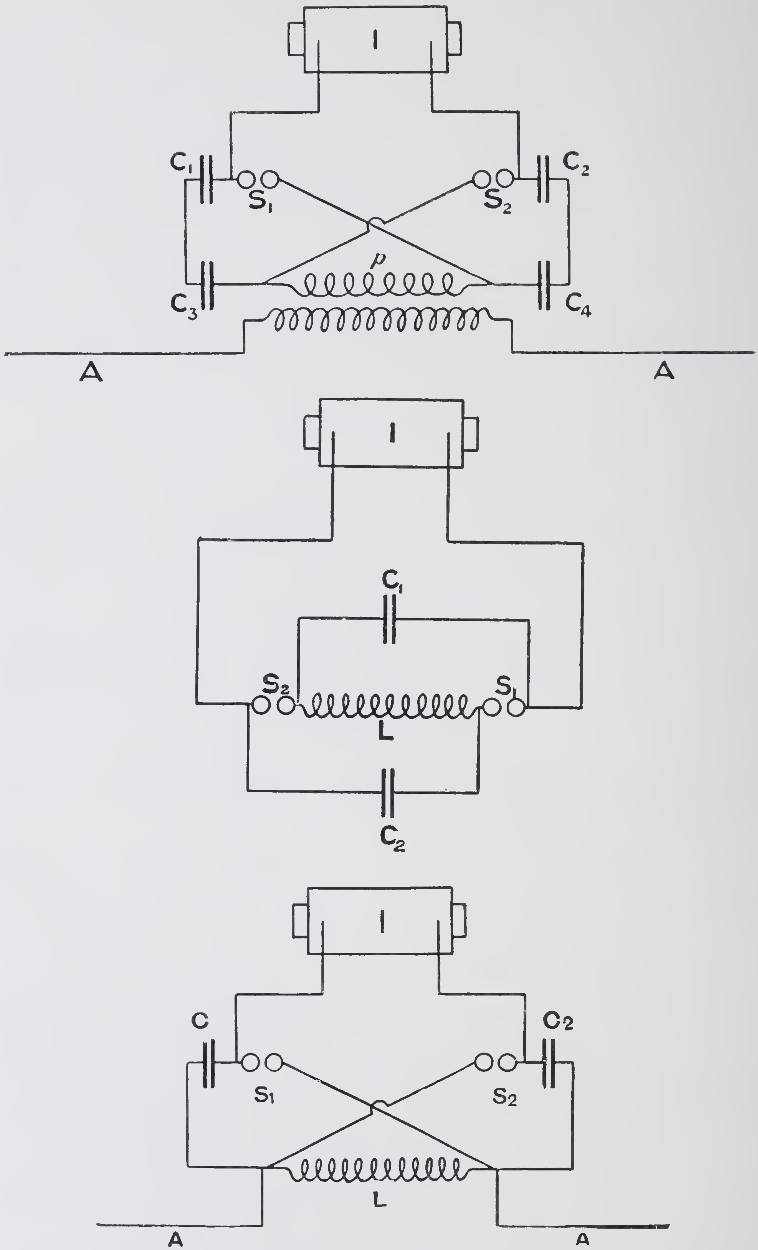


FIG. 78.—Lesemann's Method of Charging Condensers in Series and Discharging them in Parallel from an Induction Coil. I, induction coil; C_1, C_2, condensers; S_1, S_2, spark gaps; L, inductance coil; p, s, oscillation transformer; A, antennæ.

The advantage to be gained by the use of relatively small capacity in the primary oscillation circuit is shown by the following example. Let us suppose that the primary capacity $C_1 = 0{\cdot}1$ mfd., and that the primary inductance $L_1 = 10^5$, and that the spark length used is 1 cm. corresponding to 30,000 volts. Then the frequency n is 5×10^4, and if the spark be assumed to have a resistance of 1 ohm the resistance decrement δ is 0·05.

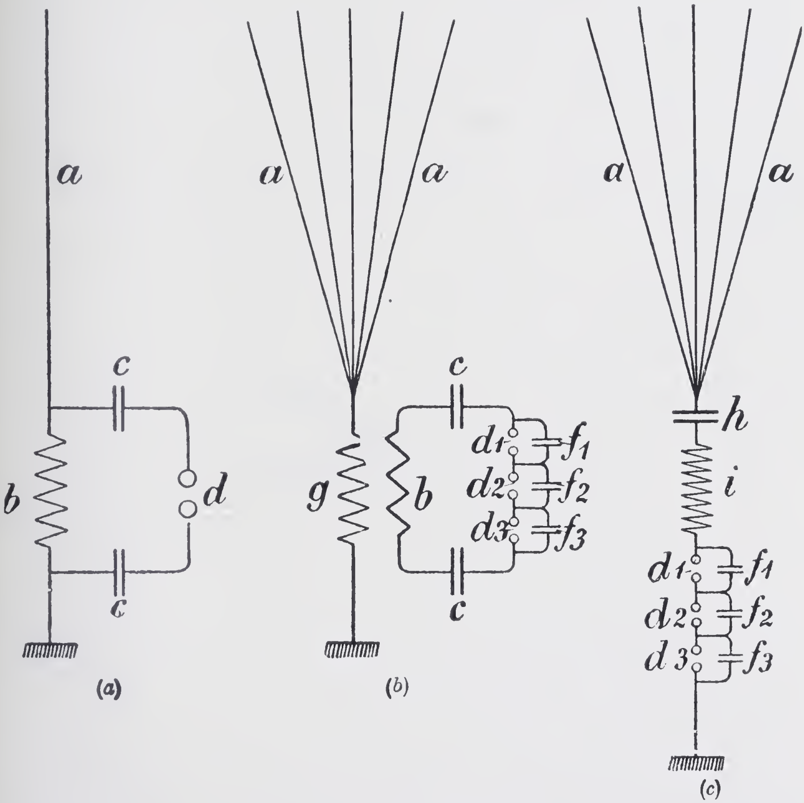


FIG. 79.—Methods of Employing a Subdivided Condenser, f_1, f_2, f_3, and Multiple Spark Gap, d_1, d_2, d_3, in Connection either with a Directly Coupled Antenna as in (*a*), or an Inductively Coupled Antenna, as in (*b*), or a Simple Antenna, as in (*c*), to obtain a Smaller Resistance Decrement, and therefore more Persistent Oscillations in the Condenser Circuit.

If, then, we divide the condenser, say, into five parts, and arrange these in series, each with a spark gap of 1 cm. in length and a separate discharge path for each condenser, having an inductance, say, of 1250 cms., the frequency of the oscillations will rise to 10^6, and yet the whole stored energy will be the same. If the main discharge circuit has still an inductance of 10^5 cms., we shall then, by the mere fact of raising the frequency, find we have lowered the decrement to 0·0125, or to one quarter of its original value. Hence, without

affecting the quantity of the stored energy, we have yet made the number of oscillations per train much greater.

The arrangement of the capacity of the primary condenser is not, therefore, a matter of indifference, and with a certain capacity at disposal we can make use of it by certain arrangements more advantageously than by others.

18. Signalling Keys.—Another element of practical importance in the transmitting apparatus is the signalling key. In order to create the signals it is necessary to be able to close the primary circuit either of the induction coil or alternating current transformer used to charge the primary condenser for longer or shorter time, in accordance with the signals of the Morse alphabet. This is done by means of a primary key. When using an ordinary 10-inch induction coil, the primary current which has to be interrupted is a current of about 10 amperes. This can be easily done by means of a Morse key, having heavy platinum contacts and a long insulating handle. In

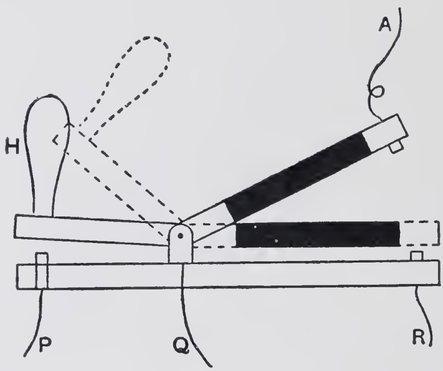


Fig. 80.—Marconi Signalling Key arranged to Automatically Disconnect the Antenna from the Receiver before Signalling. A, connection to antenna; R, connection to receiver circuit; P, Q, connections to primary circuit of induction coil. The black portions are ebonite.

order to quench the spark at the platinum contacts a large condenser may be placed across the break points, or else a magnet may be employed as a magnet blow-out to destroy the arc which tends to form on separating the points.

Mr. Marconi has devised a key for induction coil working which renders it impossible to commence working the spark coil until the aerial is disconnected from the receiving apparatus. This key is shown in Fig. 80, where the black portions represent ebonite. When the key is not in use it rests on its back contacts, and the antenna is connected to the receiving instrument, ready, therefore, for reception. But as soon as the operator commences to send signals it automatically disconnects the antenna from the receiving instrument.

When alternating currents are employed to excite either an induction coil or an alternating current transformer, keys are now employed which are practically sparkless, because the contact cannot be broken until the instant when the current in the primary circuit passes

through its zero value. This is achieved by making the primary current pass through an electromagnet, which slides down the contact piece when once it is pushed down by the key, and the raised circuit is not broken again, even if the key is resting, until the primary current passes through its zero value.

In the method of signalling devised by the author, a pair of choking coils are interposed between the alternator supplying the alternating current supplying the transformer or battery of transformers. The signals are made by short-circuiting one or both of these choking coils. A convenient way of doing this is to divide the choking coils into a number of sections. These sections are connected to metal pins carried on a long rocking arm (see Fig. 66, Chap. VII.), each pin being shorter than its neighbour, the whole group being arranged like a series of pan-pipes. If this group of pins is plunged into mercury, it short-circuits the sections of the choking coil one after the other, and not simultaneously. The rocking arm can be worked by the arrangement already described in Chap. VII. (see § 16). The arm is pivoted at one point, so that one arm, viz. that to which the pins are attached, is much longer than the other. To the end of the short section is attached a strap or tape, which lies loosely on the pulley of an electric motor, which is rapidly rotating. Over this strap rests a jockey pulley, carried on another lever, which can be depressed by the attraction of an electromagnet. As long as the jockey pulley does not press hard upon the tape it does not grip the motor pulley, but very little pressure upon the jockey pulley cast for energizing the electromagnet will cause the strap to bite upon the motor pulley, and it is then rapidly wound up, causing the lever carrying the pins to be depressed. The magnet can be energized by means of the current, which is given the required intermittency by means of a strip of punched paper tape on which the signals to be transmitted have been punctured. This punched tape is made to travel by clockwork over a wheel, and a little contact point drops through the holes in the tape and closes the electro-circuit of the electromagnet for a longer or shorter time, according as the hole in the punched tape is a dot or a dash. By this arrangement the signals impressed upon the tape are repeated by the main key, and a large alternating current can be started or stopped in the primary circuit of a bank of transformers.

To keep the mercury in the vessel into which the pins dip from volatilizing, it is necessary to flow a current of cold water over it, but if this is done the arrangements act very perfectly, and are capable of sending with far greater ease and certainty than by any hand key.

Another method of signalling with syntonic apparatus is to throw the secondary or antenna circuit into and out of tune by the insertion of inductance, or to short-circuit the condenser in the spark circuit by an impedance coil. This last method is to be preferred, as it intermits the spark. There is but little doubt that automatic sending by punched tape will for power station purposes supersede hand sending entirely.

The type of signalling key mostly used in small and large power stations on the spark system is the relay key, in which a small continuous current is manipulated by an ordinary telegraph or Morse

key. This current serves to actuate an electromagnet which closes the circuit of the alternating currents in the charging transformer primary circuit.

This last key is of the type shown in Fig. 61, Chap. VII., in which the contact when once made is kept closed until the alternating current passes through its zero value, when it opens without spark if the signalling key is raised.

CHAPTER IX

RADIOTELEGRAPHIC STATIONS

1. Radiotelegraphic Stations and Systems.—In this chapter we shall consider the combination of the appliances, which have already been described in detail in the previous chapter into the complete plant as employed for the equipment of modern radiotelegraphic stations for electric wave wireless telegraphy. We may classify radiotelegraphic stations under four principal heads: (i.) Coast stations for small or moderate distances; (ii.) Ship stations; (iii.) Long-distance or power stations; and (iv.) Portable stations for military or experimental work.

There is, of course, no sharply marked distinction between the short-distance and long-distance stations. Generally speaking, it may be said that stations having a range of 200 or 300 miles would be called short-distance stations, and stations from 300 to 3000 miles or more, long-distance stations.

The various types of complete radiotelegraphic plant may be broadly classified also into four divisions as regards transmitters.

(i.) Slow speed damped train spark methods with sparks—25 to 100 per second—employing a directly charged antenna (Marconi original system) or an energy storing oscillation circuit coupled directly or inductively to the antenna circuit and syntonized to it (Marconi subsequent system).

(ii.) High speed damped train spark methods with sparks several hundreds or thousands per second (musical sparks) by rotating Marconi dischargers or other methods.

(iii.) Quenched spark or shock excitation methods as by the Wien, Telefunken, Peukert, or Von Lepel dischargers.

(iv.) Undamped wave production as by Marconi rotating disc discharger, Duddell or Poulsen arc, or Fessenden high-speed alternator.

As regards receiving arrangements no very definite classification is possible. Broadly speaking, radiotelegraphic stations may be distinguished as undamped wave stations or damped wave stations with high or low speed successions of wave trains.

The prediction confidently made at one time that the arc system would supersede the spark system has not been fulfilled. The greater part, perhaps 99 per cent. or more of the radiotelegraphic work of the world, is conducted on the spark system, and for long distance commercial work nothing has proved superior to Mr. Marconi's high-speed spark system with rotating dischargers.

The exact details of the equipment of the larger radiotelegraphic stations are difficult to obtain, and, owing to improvements, are subject to alteration. Any statistics, therefore, of types of equipment are but of temporary interest. In accordance with the regulations prescribed by the International Radiotelegraphic Convention of 1906, a Bureau was established at Berne, charged with the duty of collecting and disseminating information of importance concerning radiotelegraphy to the various governments which have ratified the Convention. An official list of radiotelegraphic stations open for international traffic was issued in October, 1909, a brief epitome of which appeared in the Engineering Supplement of the *Times* for October 20, 1909, as follows :—

"The countries included are the United Kingdom, Germany, Russia, Austria, Italy, Spain, Denmark, Sweden, Norway, Belgium, Holland, Japan, Uruguay, and Chile. The catalogue does not include stations in the United States, as the Government of that country did not ratify the adhesion of its delegates to the Convention. Canada and France are also missing from the list. The particulars of each station, whether on the coast or on board ship, are entered in eleven parallel columns, and give its geographical position, call signal, normal range, system employed, wave length, nature of service—*i.e.* whether public or restricted—hours of working, and charge per word. The number of stations in the list reaches the total of 690, although the war-vessels of several of the countries are omitted. Of these 690 installations 124 are coast stations, the majority being open to the general public, and the remainder to messages from ships in distress only. In the latter class are the naval and military coast stations and those on lightships. The list does not include any inland stations, since these do not come within the purview of the Convention. The distribution of the stations on the coasts of the various countries is as follows: Great Britain and Ireland, 35; British West Indies, 4; Gibraltar, 1; Malta, 1; Italy, 23; Germany, 15; Tsing-tau, 1; Russia, 13; Denmark, 7; Japan, 5; Norway, 4; Austria, 3; Holland, 3; Chile, 3; Spain, 2; Uruguay, 2; Belgium, 1; Brazil, 1; Roumania, 1. Even without counting the British stations in Canada and elsewhere, which do not appear in the list, it is clear that Great Britain has realized that wireless telegraphy is of far greater importance to her than to any other country. In the matter of ship stations she is also well ahead, the totals for Great Britain and Germany being: Great Britain, warships, 176, merchant vessels, 86; Germany, warships, 95, merchant vessels, 53. It is interesting to note that among the coast stations in Great Britain there are four which conduct the ordinary telegraphic business of the Post Office, taking the place of a wire or cable. These stations work in pairs, one pair communicating across the Wash and the other between Mull and the Outer Hebrides. The British Post Office is therefore the first among the signatories of the Convention to use wireless telegraphy in place of the older methods as a regular means of communication."

2. **Coast Stations.**—In selecting the site for coast stations many considerations must have weight, but the locality is mostly determined by the nature of the work to be done, which is usually the establishment of communication with certain lines of shipping, or with another station across a channel. Accordingly, such radiotelegraphic stations are generally put as near as possible to the coast, frequently in isolated positions, and often situated on the summit of a high cliff. In any case a site must be selected which permits of substantial foundations for a mast and facility for erecting the same. The mast is generally a stout ship's mast constructed in three sections, and having a height of from 100 to 180 feet. In erecting the mast, if steel wire stays are employed, they must be cut up into lengths by insulators for the purpose of preventing oscillations of the same time period as the antenna being absorbed by them. One type of insulator

employed consists of a pair of balls of insulating material having grooves at right angles on them; the balls are connected by a well-tarred or paraffined rope, and the loop of the stay passes round the groove at right angles to that carrying the rope (see Fig. 1). In other cases a pair of ebonite or porcelain dead-eyes are employed, the dead-eyes being connected by a rope. The top of the mast sometimes carries a gaff, to the upper extremity of which is attached a pulley for raising the antenna. The aerial wire may consist of hard-drawn copper or phosphor bronze wire, preferably stranded. A single plain vertical antenna has not sufficient capacity for anything more than a short range, whilst the T-shape or L-shape antennæ have directive qualities and unsymmetrical radiative power. Hence a favourite form of antenna for coast stations is the umbrella antenna. This form of antenna has symmetrical radiation in all directions, but being a partly closed antenna its radiation decrement is not nearly so large as that of the single or multiple vertical antenna. Hence the oscillations in the umbrella form are more sustained, and the larger capacity bestows considerable energy on them.

Fig. 1.—Stay Insulator.

In some cases the mast is replaced by a metal strut insulated at the bottom by being carried on a slab of marble or porcelain, and is made part of the antenna. In this case the stays supporting the strut must be insulated from it. In those cases in which a conductive earth is employed, copper or zinc plates must be sunk in the ground. The best form of earth plate is a number of radiating wires or strips of copper laid underground sufficiently deep to be in damp soil. It is always advisable to put down the earth plate in two sections not very close together for the sake of being able to make resistance tests. If, instead of an earth plate, an insulated balancing capacity is employed, it may take the form of a number of wires radiating from the mast, and it is best to stretch these at a height of about 8 feet from the ground, so as to be able to walk underneath them. These wires may conveniently radiate out from the mast to short poles about 8 feet high, arranged at a distance in a circle round it, and their outer ends are strained on to ebonite insulators.

In some position near the mast a signalling house is erected, the size of which will depend upon the character of the work being done, and a residence for the operators will generally be erected in contiguity or not far from it. If the station is on the spark system, means must be provided for generating electric current for working either induction coils or transformers. If induction coils are used, then it will be convenient to have a small oil-engine and dynamo by means of which secondary batteries can be charged, these batteries being employed to operate the induction coil. On the other hand, even in quite small coast stations it is becoming customary to employ alternating current transformers. In this case an oil-engine must be put down, say, of 8 or 10 h.p., coupled direct to or driving by a pulley a small alternator, and also a direct current machine for charging cells and providing the exciting current for the alternator. This plant is conveniently kept

in one room by itself under the charge of an engineer. The alternator should generate current at a pressure of one or two hundred volts with a frequency of not less than 100 and preferably 500 or 600. For the sake of security it is better to excite the alternator by means of current from storage cells which are regularly charged by a continuous current dynamo. In this way the oil-engine may be employed to drive the direct current machine and charge the cells at times when it is not necessary to send messages. The cells then provide the current for exciting the alternator at any time when it is desired to signal. The current from the alternator is led through well-insulated leads into an adjacent room in which are placed the transformers, condensers, a spark gap, and oscillation transformers, and to which room the aerial wire is also led. In small coast stations the condensers are preferably made with metal-coated glass plates placed in oil, as described in Chap. I. § 11. In many stations a type of tubular condenser is employed consisting of a large glass tube closed at one end and coated with tinfoil inside and out to within a foot of the top, the glass being thicker between the tinfoil edges than lower down, for the sake of giving greater security from puncture. If alternating current transformers are employed they must be oil insulated transformers, raising the voltage from 150 to 20,000 or 30,000 volts, and if higher voltages are required, it is more convenient to join the primaries in parallel and the secondaries in series to give the required voltage. The spark gap should be an enclosed spark gap in a silencing chamber. A third room contains a receiving apparatus and the signalling key. It is convenient to have the switchboard in this room so that the operator when sending sees at once the voltage of his alternator and transformer and exciting current and speed of machine or frequency of alternator, and also can adjust these currents and voltages by means of appropriate rheostats and switches. He must also have a lever within reach by which he switches over the end of the antenna from the sending apparatus to the receiving apparatus. In stations on the arc system for producing undamped waves, in place of an alternator, a direct current dynamo is required giving a voltage of about 500 volts. In this case the arc apparatus, condenser, and oscillation transformer will generally be placed in the same room with the receiving apparatus, so as to be under the control of one operator. If the coast station is in communication with the General Post Office telegraph wires, then the ordinary telegraphic sending and receiving apparatus for telegraphy with wires will also be placed in the receiving room.

As a good illustration of a short distance station on the latest model, we may give the following details of the station erected by the British General Post Office at Bolt Head in South Devon, England, for communication with ships in the Channel, opened for communication by the Postmaster-General at the end of 1908. The following account is taken, by kind permission of the proprietors, from an article in the *Electrical Review* for January 8, 1909, to whom we are also indebted for the use of the illustrations.

This station, although the seventh radiotelegraph station belonging to the British Post Office, was the first one to be opened to the

public for communication with ships at sea. It is situated in South Devon, about 5 miles south of Kingsbridge, and is some 400 feet above sea-level. Its normal range of communication is 250 miles, but good communication is obtained with Scheveningen, in Holland, some 350 miles distant.

The construction and equipment of the station was carried out according to the specifications of the engineer-in-chief to the Post Office (Major O'Meara, C.M.G.), who placed contracts with the Marconi Wireless Telegraph Co. and the Westminster Engineering Co., the former for the supply of mast, aerial, etc., and the radio-telegraphic apparatus, while the latter supplied the power plant, which includes an oil-engine, dynamo, secondary battery, switchboard, and the lighting of the building.

The work, which included the erection of a single-storied brick

FIG. 2.—Bolt Head Post Office Radiotelegraphic Station.

building (see Fig. 2) to accommodate the power plant and the telegraphic apparatus, was commenced on July 15, 1908. It was opened for work by the Postmaster-General on December 11, 1908.

Mast Aerial, etc.—The mast is built of Oregon pine, and is in three sections; the lower mast being 73 feet in length, the topmast 56 feet, and the top-gallant mast 54 feet, which, with the reduction for the overlap of the housing portions, provides a total height of 161 feet.

There are three sets of four flexible galvanized iron wire rope stays, each stay being divided into sections by porcelain insulators. The lower stays are 3 inches in circumference, are divided into two sections, and are insulated at three points; the intermediate stays are $2\frac{1}{2}$ inches in circumference, are divided into three sections, and are insulated at four points; the upper set of stays are 2 inches in circumference, are divided into four sections and are insulated at five points. The separating insulators, which are shown in our view, are arranged to be in compression, so that if, for any reason, one of them

should break, the stay would not part. Means are provided for regulating the tension in each stay.

Four short poles about 30 feet in height are set some 150 feet distant from, and form the corners of, a rectangle around the mast, for the purpose of anchoring the aerial wires.

The aerial consists of two stranded phosphor-bronze conductors connected together at the operating room, but carried upward separately, one on each side of the mast. At the top, where they are attached to ebonite rod insulators, both conductors are bifurcated and all four portions are then extended radially in a downward direction to within 50 feet of the four 30-feet poles already mentioned, to which they are attached by ebonite rod insulators and rope stays.

The "earth" connection is made by means of 52 copper leads,

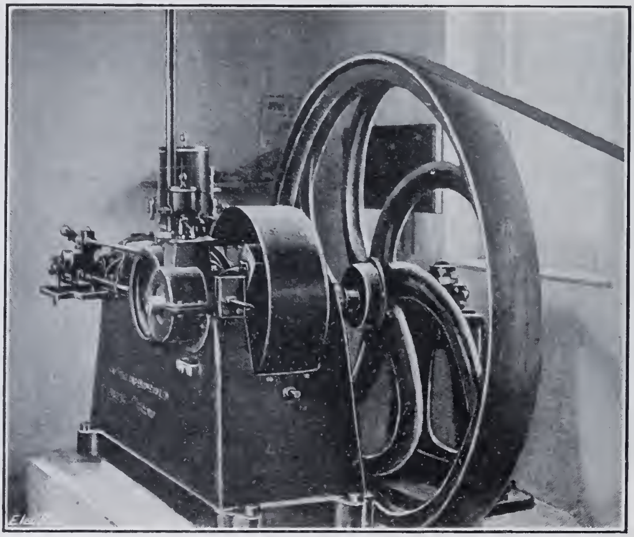


Fig. 3.—Engine in Bolt Head Station.

joined to 26 galvanized iron plates, 5 feet by $2\frac{1}{2}$ feet in area, connected together and placed vertically in the ground, and forming a portion of a circle around the operating room.

For protection against damage by lightning, a sliding ebonite rod passing through the wall of the instrument room enables the operator to directly earth the aerial outside the building by bringing the wires against a brass ring connected to the earth plate.

The Power Plant.—A Campbell oil-engine (Fig. 3) capable of developing a maximum of 10 B.H.P. when running at a speed of 265 R.P.M., is utilized to drive through a belt and friction clutch a 3-kw. direct-current dynamo, coupled direct to an alternator. The clutch is required in order to avoid the removal of the belt when the engine is not in use, and the dynamo is being run as a motor from the secondary cells; it also provides an easy means of starting the engine.

The D.C. dynamo (Fig. 4) provides current for charging the fifty-two secondary cells, for exciting the field of the alternator, and for lighting the building. It is also run as a motor from the secondary cells to drive the alternator when the engine is not in use.

The alternator furnishes 3 kw. at 100 volts, at a frequency of 50.

The various connections are taken to a switchboard placed in the instrument room within easy reach of the operator, so that he can manipulate the different switches practically without leaving his seat at the operating table. A full diagram of the connections of the switchboard is shown in Fig. 5.

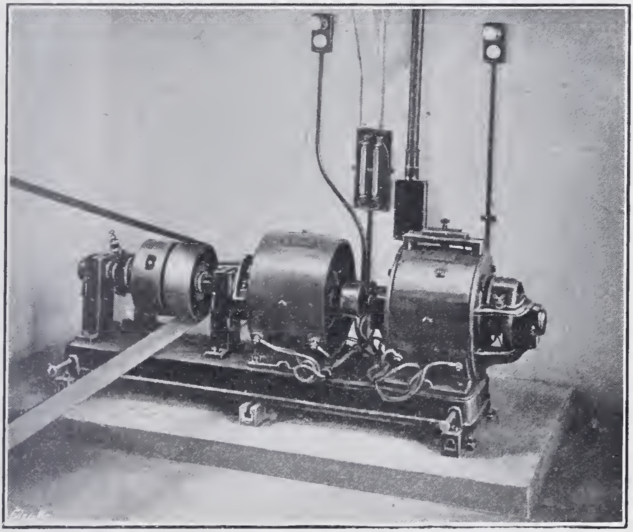


FIG. 4.—Alternator and D.C. Dynamo in Bolt Head Station.

The Radiotelegraphic Apparatus.—The switchboard connections of the radiotelegraphic apparatus are indicated in Fig. 5, and the scheme of circuit connections is shown in Fig. 6. The alternating current, controlled by means of a Morse key, is passed through a 3-kw. transformer, placed in oil. In circuit with, and forming a shunt to the contacts of the Morse key, are four "magnetic keys" joined in parallel, which open when the alternating current is passing through its zero value, thereby preventing any injurious sparking at the key contacts, and ensuring a rapid break in the current.

A means of regulating the power used is provided by an iron core adjustable inductance A.

The secondary of the transformer is connected through iron-core choke coils B, and air-core choke coils C, to the battery of condensers D. These condensers are made up of thin iron plates separated by sheets of glass and immersed in oil One side of each of the condensers is connected to the spark gap E, which is enclosed in a wooden box, while the other sides of the condensers are connected

together and through the inductance F and primary G of the oscillation transformer to the other side of the spark gap.

The secondary H of the oscillation transformer is connected on one side to the aerial, and on the other to the earth plates through a small spark gap. This small gap is for the purpose of insulating

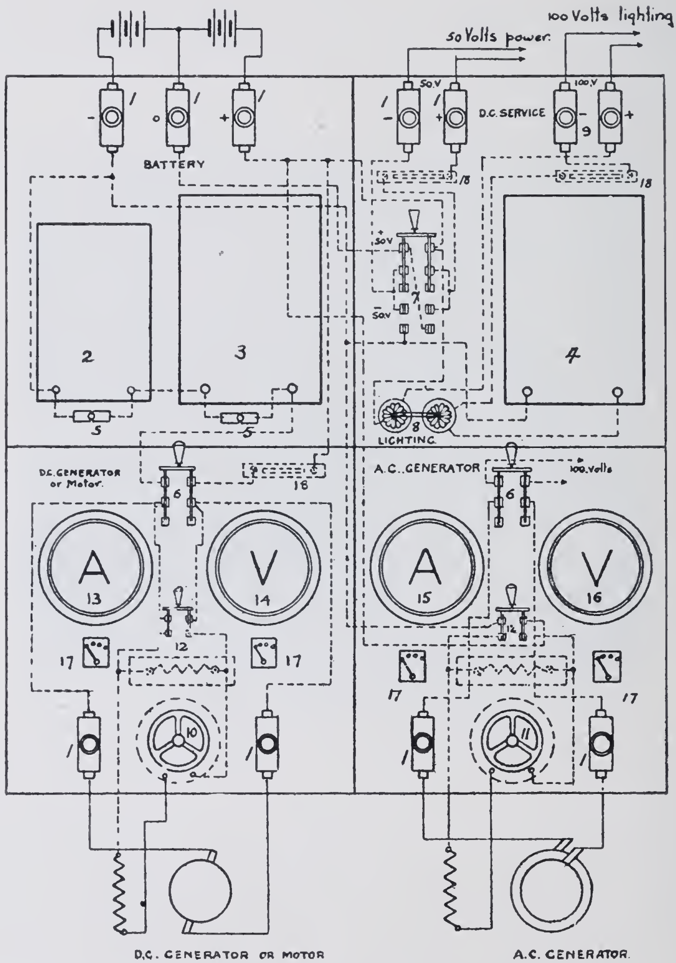


Fig. 5.—Switchboard Connections in Bolt Head Station.

the aerial in regard to received signals, whilst, as regards transmission, the spark makes the gap practically a direct earth connection.

Means are provided for varying the position of the secondary coil of the oscillation transformer in relation to the primary coil, in order to vary the strength of coupling and thereby to obtain sharper resonance.

The wave length of the transmitted signals is 600 metres, but as it may be necessary to signal with a wave length of 300 metres, a second set of condensers J, spark gap K, tuning inductance L, and oscillation transformer M is provided. Both transformers are fitted with plug connections, so that the "aerial" and "earth" leads may be readily transferred from one to the other.

With the shorter wave length, the oscillations from the 600-metre transformer charge the second set of condensers, which discharge through the second spark gap and the second oscillation transformer, to which the "aerial" and "earth" would in this case be connected.

The receiving apparatus is permanently connected to the transformer side of the small gap, which, as already stated, gives perfect insulation for reception purposes, and yet is practically a direct earth

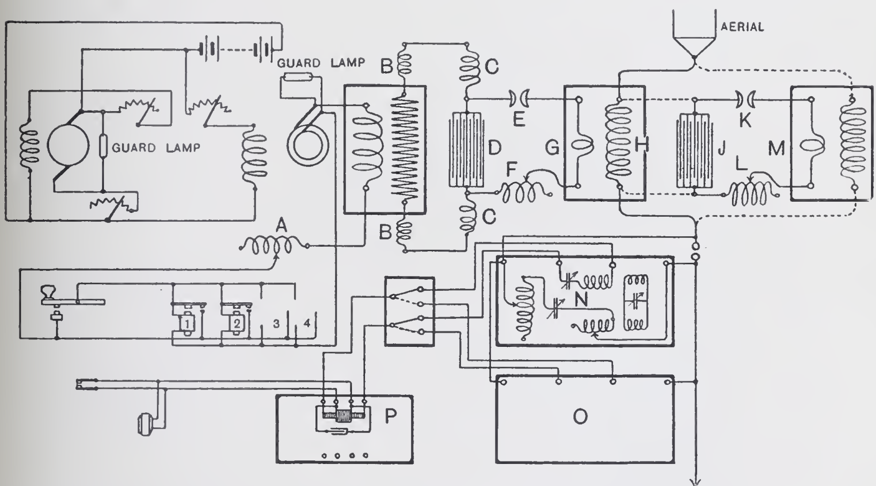


Fig. 6.—Circuit Connections in Bolt Head Station.

connection when sparks are passing. This arrangement would, however, give a loud click in the telephone whenever a spark passed, hence the Morse key is fitted with two small contacts normally separated, but which make connection and thereby short-circuit the telephone as the key is being depressed, and separate again after the sparking has ceased. Immediately these contacts open, any incoming signals pass through the receiving apparatus and actuate the telephone. Hence it is possible for the operator to be stopped in the middle of transmission if it should be necessary.

Received signals pass down the aerial through the secondary of whichever oscillation transformer is in use, to "earth" *viâ* one or other of the two multiple tuners, N or O, which are a series of adjustable inductances and capacities arranged for wave lengths of 100 to 2000 metres in one case, and for 2000 to 6000 metres in the other.

Each tuner is provided with a switch, which connects the leads of the magnetic detector P to the "stand-by" or "tuning" positions. In the former position the coil of the detector is directly in circuit with

the aerial tuning inductance, and in the latter position there is a double transformation between the aerial and the detector. The coupling of this double transformation can be varied by turning a handle at the side of the instrument. By this means it is possible to cut out to some extent the signals of another station which may be causing interference.

The magnetic detector is the well-known Marconi type of instrument, and is connected to a switch, which joins it to either tuner as desired. The headgear telephone receiver is connected to the detector in the usual way, and is also connected to the two additional contacts on the Morse key.

The coherer and Morse receiving apparatus are not used, as the station is always open and an operator is listening continuously when not transmitting.

The building (Fig. 2) is 55 feet long, 13 feet broad, and 14 feet high, and is divided into five rooms, as follows :—

Instrument-room, 11 ft. × 7½ ft.
High-tension-room, 13 ft. × 6½ ft.
Battery-room, 13 ft. × 6½ ft.
Engine-room, 24 ft. × 12 ft.
Ante-room, 11 ft. × 5 ft.

Messages are passed direct to Exeter by an overland telegraph wire.

The photographs from which these illustrations were prepared were taken by Mr. Coxon (of Major O'Meara's staff), who supervised the installation of the power plant at the station.

According to a statement made by the Postmaster-General (Mr. Sidney Buxton) in opening the Bolt Head Station, the cost of it amounted to £2000, and this may therefore be taken as an illustration of the capital outlay necessary to establish such a Coast Station capable of communicating 300 or 400 miles.

3. Ship Stations.—In ship stations equipped for radiotelegraphy on the spark system the arrangements have to be very compact because the space which can be given is generally very small. A signalling cabin is set apart somewhere on the deck, through the bulkhead of which the antenna passes in a tube of ebonite. One of the difficulties here is the sufficient insulation of the antenna at the point where it enters the signalling cabin. Through the bulkhead passes a thick solid ebonite tube about an inch in outer diameter and half an inch inner diameter. The outer end of this tube is bent downwards like the nozzle of a water tap, and the aerial wire coming from above tilts upwards and passes through this ebonite tube into the signalling room. To keep the ebonite tube dry at the place where the wire enters it, a shelter hood is put over it. In the signalling cabin the transmitter comprises a 10-inch induction coil, which is generally operated with a simple hammer break not likely to get out of order at a critical moment. As the safety of many lives may depend upon the wireless telegraph apparatus being in perfect order, even after a collision at sea, everything has to be sacrificed to simplicity and certainty of action. For this reason it is also advisable to operate the induction coil from secondary batteries which are

charged at intervals from the lighting current of the ship or from a dynamo in the engine-room. In some cases alternating current is employed with a transformer, the alternating current being provided from an alternator in the engine-room. Against this it may be said that in case of collision or accident, the main engines may have to be shut down or the engine-room or boiler-room may be flooded, and therefore the supply of current therefrom cut off just at the very moment when it is absolutely necessary that the wireless apparatus

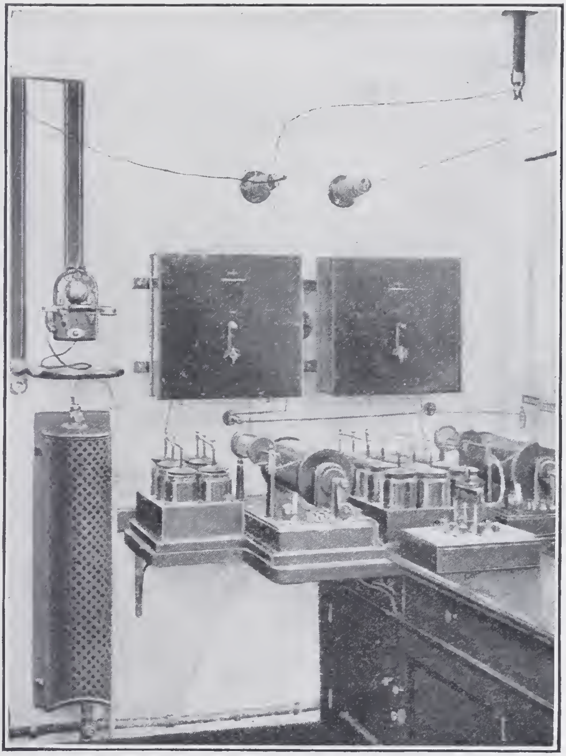


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Fig. 7.—Marconi Wireless Telegraph Transmitting Apparatus, as used on Ship Installations.

should be in perfect order. If, however, the operator has two sets of secondary batteries each consisting of eight cells, which are regularly charged alternately, the chances are largely in favour of his having a fully charged set at his disposal at any moment sufficient to work an induction coil for many hours. He is then completely independent of the engine-room.

In addition to the induction coil the transmitting set includes a tray of Leyden jars or some form of condenser and an inductance coil or oscillation transformer and spark gap. The spark gap ought

to be invariably contained in a cast-iron silencing chamber to obviate the nuisance of the noise of the spark being heard all over the vessel, or messages being read by ear when being sent, by experts outside.

In Figs. 7 and 8 is shown a view of the Marconi Company's ship apparatus as employed on the Atlantic liners and other ships equipped by them. It will be seen that two sets of Leyden jars are shown, as well as two coils, one set with about six jars and the other with a larger number. These two sets of apparatus are provided for the

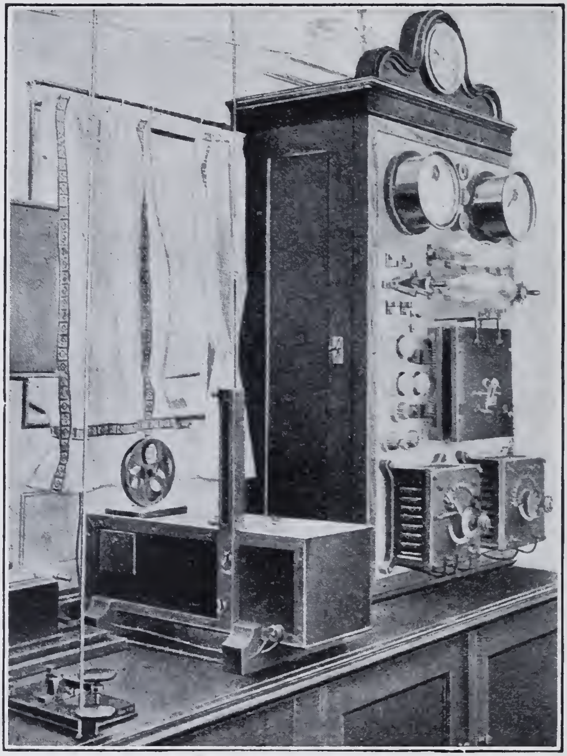

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FIG. 8.—Marconi Wireless Telegraph Receiving Apparatus, as used on Ship Installations.

sake of being able to produce waves of two wave lengths. The receiving apparatus on ship and coast stations comprise a coherer and tapper as an oscillation detector associated with a relay and a Morse inker for printing the messages on the telegraphic tape, or else an oscillation detector such as a Marconi magnetic detector, in the case of the Marconi Company installations, but in other cases may be used an electrolytic detector, a Fleming oscillation valve, or any of the contact detectors described in Chap. VI., the signal producing instrument being then a telephone. The operator wears

on his head a double-headed high resistance telephone, which is connected with the oscillation detector. He has within reach a lever for switching over the antenna from sending to receiving, and also the key with which he sends. If the transmitting plant is a simple induction coil operated with direct current, the key is merely a heavy Morse key inserted in the primary circuit of the induction coil. If, however, the current is an alternating current, then the key may be either a relay key opening and closing the primary circuit of the alternating current transformer, or one operating a lever which cuts the condensers in and out of the circuit; or an electromagnetic key which short-circuits part of the inductance in the primary oscillation circuit, and so alters the tune or wave-length of the waves radiated.

When using the telephone as a signal receiving instrument the operators are much assisted by the adoption of a suitable spark frequency and syntonized telephone. The sound made in the telephone on depressing the signalling key is really a series of very short sounds, each of which is produced by a single spark at the spark balls of the distant transmitter. Hence the note that is heard in the telephone is the result of the rapid reiteration of these short sounds. If the spark frequency is uniform and anything above a hundred per second, then, when the signalling key is continuously depressed at the transmitting station, the operator at the receiving end hears a musical note at the telephone corresponding to this spark frequency. This note only has a true musical character if the time interval between the sparks is perfectly uniform. As we have seen, this is very far from being the case when an induction coil with an ordinary or mercury break is employed, but when an alternating current transformer is used, then much greater uniformity in the spark frequency is possible. The ordinary telephone receiver is most sensitive, according to the researches of Lord Rayleigh and M. Wien, for some frequency lying between 500 and 1000. This is because the telephone diaphragm has a natural rate of vibration of its own, or rather a fundamental rate to which it responds best. Thus, Lord Rayleigh (see *Phil. Mag.*, vol. 38, 1894, p. 285, and "Theory of Sound," vol. i. p. 473) measured the alternating current in microamperes required to produce the least audible sound in a telephone receiver of 70 ohms resistance at various frequencies, and found values as follows:—

Frequency	128	192	256	307	320	384	512	640	768
Least audible current in microamperes	28	2·5	0·83	0·49	0·32	0·15	0·07	0·04	0·1

M. Wien found for a Siemens telephone somewhat different results, viz.—

Frequency	64	128	256	512	720	1927	1500
Least audible current in microamperes	12	1·5	0·13	0·027	0·008	0·013	0·024

Both, however, agree in finding a maximum sensitiveness for currents of a frequency between 600 and 700. This is due to the fact that the frequency of the actuating current then agrees approximately with the natural frequency of the ordinary size of telephone diaphragm.[1] Hence, alternators for large-power radiotelegraphic stations are now designed to give currents with a frequency of about 300 or 600 alternations per second, so that when producing discharges of a condenser, the number of sparks per second may be at least 600, and fulfil the conditions for giving maximum sound in the telephone of the receiver per microampere.

Accordingly, by the adoption of this spark frequency, the sound made in the telephone is not only the loudest, but its musical character enables the operator to distinguish clearly between the sounds in the telephone, constituting the Morse signals, for which he is listening, and other sounds, irregular and often of a lower note, which are due either to atmospheric electric disturbances, or to vagrant waves of some other stations. The human ear possesses the peculiar power of paying attention to sounds of high pitch, and disregarding those of lower pitch which may be affecting it at the same moment. Attention has been drawn to this by R. A. Fessenden (see U.S.A. Patent No. 918,307, of 1908), and previously by Lord Rayleigh, in 1907 (see *Phil. Mag.*, November, 1907). Fessenden states (*loc. cit.*) that, with a spark frequency of 900, messages can be read with great ease by telephone; when at a frequency of 250 they are unintelligible by reason of disturbing atmospheric discharges. One of the important characteristics of Marconi's high-speed rotating dischargers are that they can impart this high-pitched musical character to the sounds made by the distant spark in the telephone at the receiving end. It is also one of the advantages claimed for the quenched spark system when using a high frequency alternator. It is partly for this reason that the method of reception by telephone and ear has so largely superseded the method of receiving signals by the Morse printer, because the coherer detector used with the printer cannot distinguish between various classes of waves affecting the antenna in the same way that the human ear can, and it is therefore much more difficult to keep the true signals free from confusion by the interpolation of marks on the tape, due to atmospheric discharges, to which further reference is made in § 8 of this chapter.

4. Power Stations.—The power stations or long distance radiotelegraphic stations do not differ in essential principle from those on a smaller scale, such as ship and coast stations; but they differ in the magnitude of the appliances used. Apparatus which in a certain form may be called physical or laboratory apparatus has to be converted into engineering plant suitable for continuous work under all conditions of weather and time. The locality of a long distance station will generally be settled by the work to be done. In selecting the site for his transatlantic stations, Mr. Marconi was naturally desirous of shortening the distance as far as possible between two stations in correspondence. Hence, after preliminary

[1] Partly also, perhaps, to the fact that the ear like the eye is not equally sensitive to all frequencies. The eye appears to be most sensitive to vibrations of a frequency of 550×10^{12} and the ear to a frequency about one billion times less.

experiments, as already described, made at Poldhu, in Cornwall, England, and Cape Cod, Massachusetts, U.S.A., sites were selected on the west coast of Ireland at Clifden, in Connemara, and another at Glace Bay, in Nova Scotia. One consideration, which certainly ought to have weight in selecting the site for a large power station, is the liability to attack in case of war. The antenna of a power station must be carried by high towers two or three hundred feet in height, and these, of course, are very conspicuous objects for a considerable distance off the land. As modern naval guns will carry shells ten miles or more, it is obvious that an enemy's ship might attack a power station when it was considerably out of range of smaller guns on the coast. Hence, sites should be selected for long distance transoceanic stations which will preserve them from being the object of attack in case of war, when they might be of enormous use in communication with the national navy. A second important consideration will be the nature of the ground in reference to the possibility of erecting the high masts or towers, and also the possibility of obtaining easily water and coal for steam-engines and boilers. Hence, such a station should not be too far removed from railway systems.

The site having been selected, the next step is the erection of the antenna supports. These are generally constructed of wood or iron lattice towers, those at Poldhu being a good example of the former, and that at Nauen, near Berlin, of the latter. Wooden towers may be constructed by bolting together a number of planks which break joint with one another, and are cross-braced by similar diagonal braces (see Frontispiece). Such towers have to be stayed with steel hawsers broken up into sections by insulators. In Paris use has been made of the Eiffel Tower for supporting the antenna of a large subterranean station near the base. If the antenna is to be of the umbrella form, a single tower suffices. If, however, it is to be a directive antenna, such as Marconi's, then at least two towers are required to support the vertical portion, and a number of masts placed in line to support the horizontal portion. As the erection of masts is a well-understood matter, it is unnecessary to give any details under this heading. The design and erection of a tower, whether in wood or metal, is a special piece of constructive work for which the aid of the civil engineer is generally necessary.

The station buildings are, of course, erected in close contiguity to the base of the masts or towers, and must comprise an engine and boiler house, if steam is used, or engine and oil store, if oil is used; a transformer room; a condenser and oscillation transformer room, containing also the discharger if on the spark system, or the arc apparatus if on the arc system; and, of course, the receiving and operating room from which the messages are sent and received.

As regards the source of power, it is always desirable to employ steam engines if possible, as the turning moment of the alternator is then most uniform. The great objection to the oil engine as a source of power is that the load may be thrown on the engine by depressing the signalling key during the back stroke of the engine, or between explosions, and the result is then to impress a retardation on the engine. If oil is used, the engine ought certainly to be a high-

speed multiple cylinder engine, securing a tolerable uniformity of turning moment. There is a certain advantage in the use of slow-speed steam engines with large fly-wheels, owing to the larger reserve of mechanical power stored up.

Where large supplies of water are available and a steam engine is used, it will, of course, be worked condensing. As the work is irregular, it is advisable to employ boilers of the water tube or locomotive type in which steam can be raised quickly. If the station is on the spark system the steam engine is employed to drive one or more alternators, the frequency of which ought not to be below 100 and preferably 500 or 600, unless some form of discharger is employed which multiplies spark frequency. The alternator should be of that type in which the armature is the fixed portion and the rotating portion the fields, and it should be excited by the current from secondary batteries which are charged at intervals by the current from a continuous current dynamo. The alternating current may be generated at 1000 or 2000 volts and then raised in pressure to a much higher voltage, 20,000 volts or more, by means of oil insulated transformers. It is better to have transformers of not too high a voltage, say 20,000 or 30,000 volts, and join the secondaries in series and the primaries in parallel rather than to have transformers of exceedingly high voltage in each instance. Oil insulated transformers are absolutely essential to prevent brush discharges in the interior destroying the insulation. Wires are laid from the alternator and transformer rooms to the operating room, so that indicating instruments, voltmeters, and ammeters may be placed there showing the operator at any instant the current coming out of his alternator, its voltage and frequency. It is generally best to separate the engine and boiler room a considerable distance from the transformer house, and also to separate the transformer house some distance from the condenser house. In this way any accident in the condenser house causing fire will not be so likely to spead to the transformer house, and in the same way any accident to the engine in the boiler room will not be so likely to damage the transformation and condenser plant. All parts of the plant must be, of course, duplicated or triplicated, so as to provide perfect security for continuity of working and opportunity for executing repairs. In fact, the arrangements of this part of the plant are simply those of a first-rate electric supply station, with the exception that the alternating current is supplied at a much higher voltage and higher frequency than is desirable in the case of lighting or power supply.

The condensers in the case of the spark system will consist of a number of stoneware boxes containing metal plates separated by glass plates, the whole immersed in insulating oil, as described in Chap. I. § 11, or, where space is not of much importance, air condensers can with advantage be used, consisting of sheets of galvanized iron or zinc suspended on insulators six inches and a foot apart, these air condensers being joined up in series and parallel to give the required capacity and energy storage. On the arc system the condenser is, of course, much smaller, and may be an oil condenser constructed of metal plates in oil, or a compressed air condenser, but in any case should be one in which the dielectric used

has no energy absorbing quality. If the antenna is inductively coupled to a reservoir circuit, the oscillation transformer will have its primary circuit in series with the spark gap and the condensers, and its secondary circuit in series with the antenna and balancing capacity. This oscillation transformer generally consists of highly insulated finely stranded wire wound on a wooden frame, the two circuits being separated from one another by glass plates or ebonite cylinders, and the whole immersed in high insulating oil. It is of the utmost importance that the circuits of this oscillation transformer, and also of the connections of the condensers with one another and with the spark discharger, should be constructed of a suitably stranded tape consisting of high conductivity wire not thicker than No. 40 S.W.G. single cotton-covered and twisted together into a plaited tape of sufficient width. The lowest possible ohmic resistance should be obtained in all parts of these circuits, and the high frequency resistance kept down by laminating, as above described, the conductors. The use of thick strips of metal or ordinary stranded cables for connection is a great source of energy waste in the oscillation circuits.

It will generally be necessary to insert certain choking coils in the primary circuit of the high tension transformers between them and the alternator, and also in the high tension circuit of these transformers between their secondary terminals and the spark gap. The circuit which includes the secondary circuit of the supply transformers, the condenser, and the primary circuit of the oscillation transformer, must be tuned to the frequency of the alternator; that is to say, to a comparatively low frequency, and this is done by inserting appropriate inductance coils close to the high tension terminals of the exciting transformers, and these choking coils serve the additional purpose, preventing oscillations during a discharge of the condenser travelling back into the exciting transformers. On the other hand, the circuit which contains the condensers, the primary and oscillation transformer, and the spark gap, must be tuned to the frequency of the antenna circuit comprising the capacity of the antenna, the secondary circuit of the oscillation transformer, and the earth wire. Proper means must be taken to prevent the establishment of any arc discharge across the discharger by employing either the Marconi rotating dischargers, or some other equivalent device. The signals are made in the case of the power plant, either by short-circuiting one of the chokers H^1, H^2 in the low-tension side of the supply transformers, as shown in Fig. 9, or else by short-circuiting a section of an inductance in series with the condensers, or by cutting out some of the condensers so as to throw the condenser or reservoir circuit out of tune with the antenna. In any case, as little change in wave intensity should be made as possible; that is to say, a sufficient change should be made in the intensity of the emitted waves to cause the receiving station in correspondence at a distance to receive the necessary intelligible Morse signals. A large throw-over switch is generally worked by a lever, by means of which the operator changes over the antenna from sending to receiving; but as this involves considerable waste of time, devices have been invented for duplexing the antenna and using it simultaneously for sending and receiving.

Reference is made to this important matter in the next section of this chapter.

5. Existing Long Distance Radiotelegraphic Stations.—As an example of the general arrangements of power stations the following details may be given of those erected by Mr. Marconi for the Marconi Company, one at Clifden in Ireland, and the other at

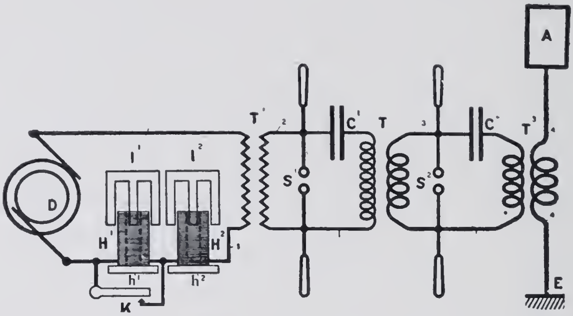

Fig. 9.—Apparatus for Multiple Transformation of Oscillations (Fleming).

Cape Breton, in Nova Scotia. A general view of the Clifden station is shown in Fig. 10, the engine and boiler house being on the right-hand side of the figure, and the condenser house in the centre with the antenna masts above it and stretched away from it, and a residence for the operators in the foreground. The total engine power installed for spare and use is 1100 H.P.

The antenna at Cape Breton and Clifden consists of a number of wires rising 220 feet vertically, supported by masts, and then extending 1000 feet horizontally at a distance of 180 feet above the ground. The antenna is designed for a wave length of about 12,000 feet. The condenser used has a capacity of 1·8 microfarad, and the spark length used is generally 18 to 20 mm., equal to a voltage of nearly 46,000 volts. The bent antennæ at Glace Bay, Nova Scotia, and Clifden, Ireland, are placed with their free ends pointing directly away from one another. The transmitting antenna contains 60,000 feet of wire, and the receiving antenna 18,000. The former is in the shape of an attenuated fan, 200 feet being vertical and the remainder horizontal, and has an area over all of about one-tenth of a square mile. The condenser employed is an air condenser formed of 1800 sheets of metal, 30 feet by 12½ feet, hung up on insulators, thereby avoiding the dissipation of energy inseparable from the use of glass condensers, and also the risks of stoppage of work involved in the puncture of a solid dielectric. The dischargers used as spark gaps in these stations are the high-speed revolving disc dischargers invented by Mr. Marconi, already described, which permit of signalling at as high a rate as hand-sending can accomplish. Owing to the regularity of the discharges, the Morse dash is heard in the telephone at the other side as a clear musical note, and the operator can distinguish easily between it and the irregular sounds due to atmospheric discharges. Fig. 11 shows the interior view of the engine and alternator

house, in which at first was used a high-speed engine coupled directly to an alternator with revolving field magnets and fixed armature

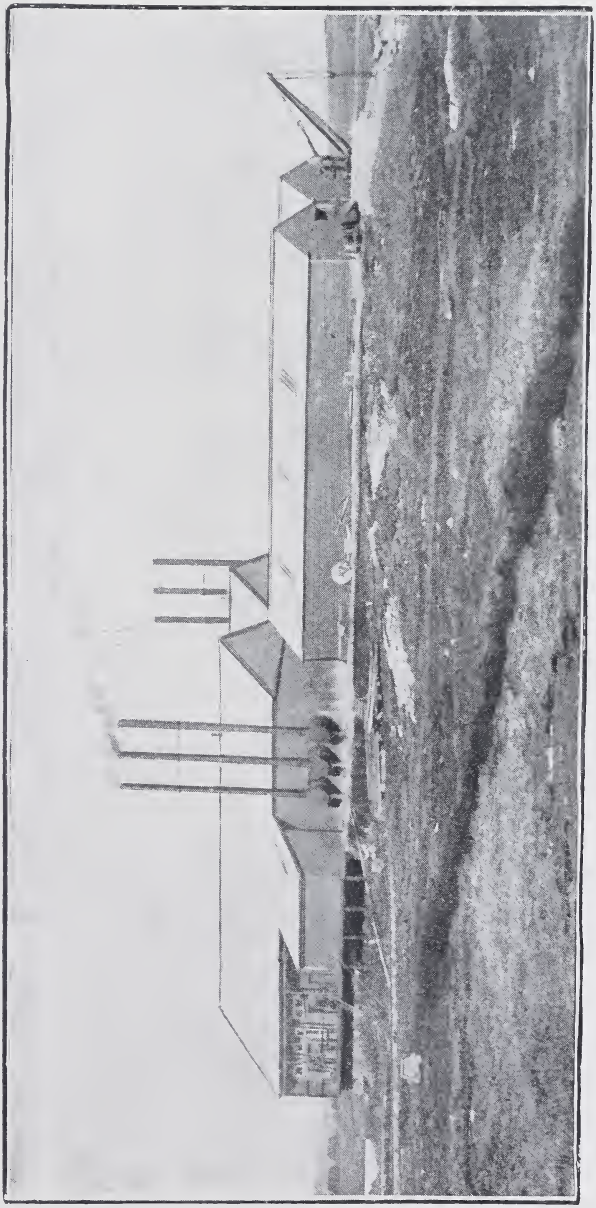

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FIG. 10.—View of the Engine and Boiler-house of Marconi's Transatlantic Radiotelegraphic Station at Clifden, Ireland.

made by the Electric Construction Company. The current from this alternator, generated at about 2000 volts, was raised in pressure by a

series of high-tension oil insulated transformers, and employed with a high-speed Marconi discharger, as shown in Fig. 70 of Chap. VIII.

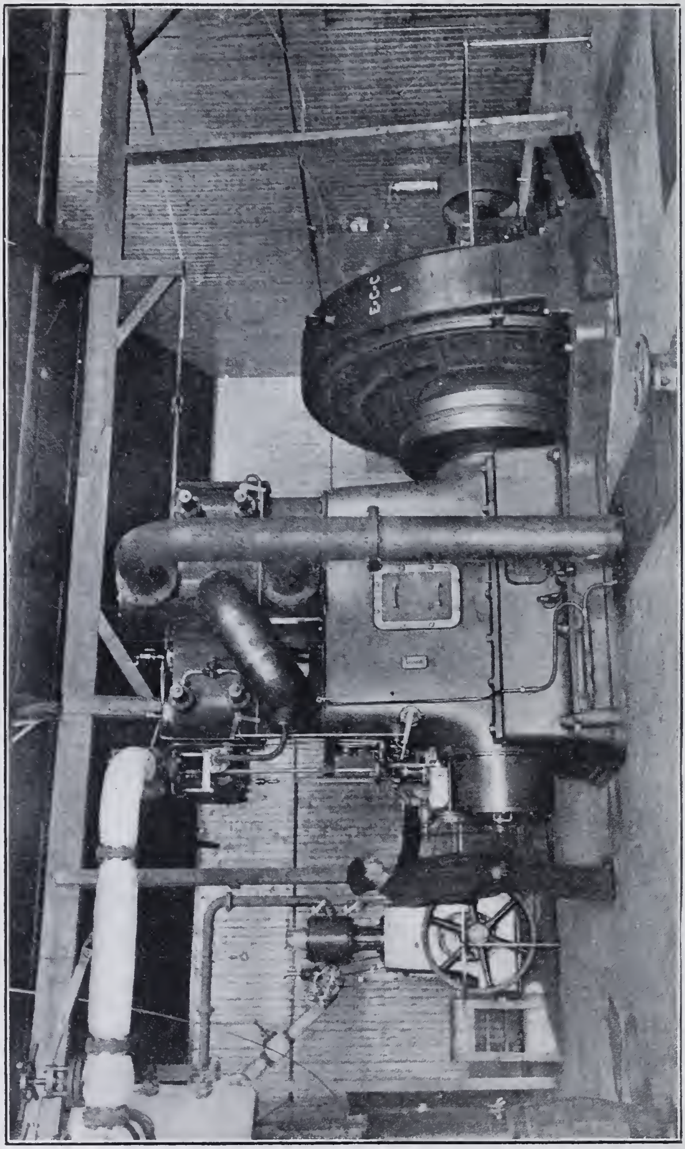

FIG 11.—View of the Engine and Alternator Room in Marconi's Transatlantic Radiotelegraphic Station at Clifden, Ireland.

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At the present time continuous current high-tension dynamos are employed to generate a continuous current for use with the Marconi high-speed rotating dischargers, and gives very good results. The

receivers employed are either the Marconi magnetic detector or the Fleming oscillation valve used with the circuits devised by Mr. Marconi (see Fig. 44, Chap. VI.). These large stations at Cape Breton and Clifden began to exchange radiotelegraphic messages across the Atlantic on October 7, 1907, and hundreds of thousands or millions of words in press and private messages have since been transmitted. The long history of this great achievement was related by Mr. Marconi in a lecture at the Royal Institution of Great Britain, delivered on March 13, 1908, in which he recounted the various stages of the work and the steps by which success had been finally attained. After an interval of interruption due to a fire which destroyed part of the

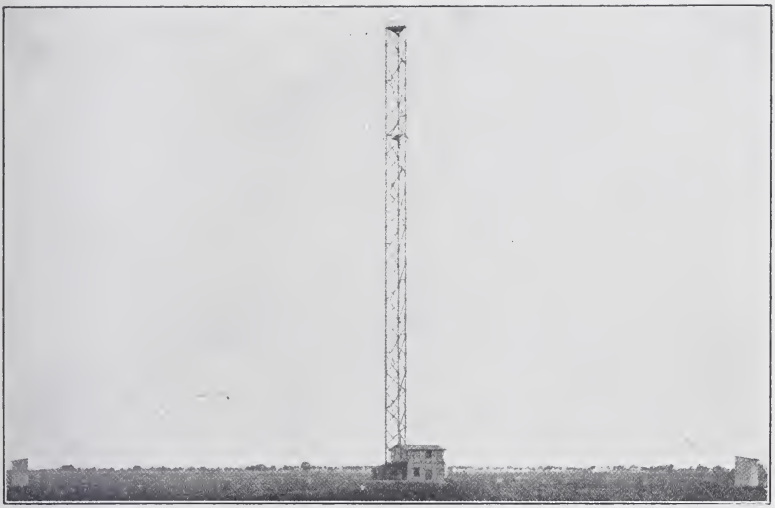

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FIG. 12.—Wireless Telegraph Mast at Nauen, near Berlin.

Glace Bay station in August, 1909, commercial communication was re-established across the Atlantic at the end of April, 1910.

As an instance of a Continental long-distance station we may briefly describe that at Nauen in Germany, within 40 kilometres of the north-west of Berlin, in the vicinity of the small town of Nauen, where the Wireless Telegraph Company of Germany has erected a powerful spark telegraph station. The antenna is of the umbrella type, supported by an iron lattice tower 100 metres, or 325 feet in height (see Fig. 12). The station is situated in a plain extending for several miles round. The nature of the ground is very suitable for a radiotelegraphic station, as it is moist, thus considerably facilitating a good earth connection. This, however, added to the difficulty of making foundations for the tower. The iron lattice tower has a triangular section with sides about 4 metres, or 13 feet, in length. The three vertical sides of this tower are constructed in lengths of 8 metres, screwed together and joined by means of diagonal stays to

each other. At the bottom these beams converge on to a ball of cast steel placed in a socket in a foundation plate, thus forming a huge hinge joint. This bed plate is insulated from the concrete foundation on which the tower rests, and the tower itself thus takes part in the functions of the antenna. At a height of 96 metres there is a small platform for working and controlling the three pairs of pulleys placed at the top and serve for lifting up the aerial wires. At a height of 75 metres three stays are attached to the tower, sustaining it in a vertical position. These stays consist of iron rods jointed together by means of strong hinge joints, and attached at the lower ends to anchors fastened at a distance of about 200 metres from the base of the mast. Both at the top and at the bottom these rods are insulated from the tower and from the anchors. In view of the great electric tension, the three upper insulators are immersed in oil. The lower fastenings of the three stays have for their anchorage large blocks of brickwork. From the top of this tower extends a system of wires which forms an umbrella-shaped antenna composed of six parts arranged in such a way that the weights of the two opposite sections are balanced against each other. This arrangement equilibrates the stresses due to the weight of the network upon

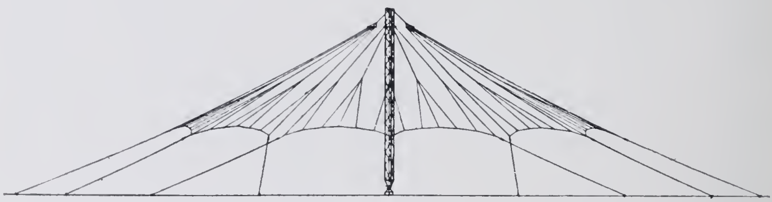

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Fig. 13.—Umbrella Antenna at the Nauen Radiotelegraphic Station.

the tower, as they are lowered or raised in pairs. On the other hand, arrangements have been made for lowering each of the segments independently if necessary.

The antenna is composed of bronze wires branching out and increasing in number from top to bottom (see Fig. 13). The whole surface of these wires is 60,000 square metres. Each separate segment of this umbrella-shaped network is fastened to the ground by means of hemp cables passed through a series of porcelain insulators and attached to anchors. All the conductors of the antenna are carried from the top of the tower to the station building, the conductors passing along the tower and entering the station building. These conductors are not separated from the tower by any insulators, the tower being thus part of the antenna. The earth plate consists of a large number of branching iron wires, arranged star fashion underground, and divided up like the antenna itself. These earth wires extend over an area of 126,000 square metres. They converge to a central point and pass inside the station building.

The station is a two-storied building, occupying an area of 100 square metres. It is divided into an engine and a telegraphic room,

and also contains dwelling apartments in the basement, and a condenser room on the first floor. The heating of the premises is effected with exhaust steam from the engine.

The prime motor is a 25-h.p. steam-engine, working at 120 R.P.M. Coal and coke are used for fuel. Water is obtained directly by pumping from the soil. The engine drives by means of a belt a single-phase alternator excited by a direct coupled exciter. This generator produces alternating current at a frequency of 500 periods per second. In the adjacent room is a switchboard, on which are the controlling switches, fuse, and measuring instruments. The system now employed at Nauen is the quenched spark system, as developed by the Telefunken Wireless Telegraph Co. The discharger consists of a series of eleven copper boxes cooled with water, each having a perfectly flat silvered copper surface, the adjacent surface being separated by very thin rings of mica, so that they are within about 0·25 mm. of each other. This discharger is placed across the secondary terminals of the high tension transformer, and to these terminals are also connected a condenser having a capacity of about 0·1 microfad, and an inductance, which at one point is connected inductively with a coil in series with the antenna. At each spark of the discharger an impulse or shock is given to the antenna which sets up in it free vibrations, and these impulses occur at the rate of about 1000 per second, thus sending out from the antenna rapidly succeeding trains of feebly damped waves. The current (R.M.S. value) into the antenna amounts to about 50 amperes, sufficient to heat a carbon rod the thickness of an ordinary lead pencil to white heat.

The receiving arrangements are as shown in Fig. 14. They comprise the usual oscillation transformer with variable coupling connecting the antenna to the reservoir circuit of the receiver, which last includes a condenser of variable capacity. The wave detector used is the galena-plumbago point rectifying detector consisting of a plumbago point pressed against a small mass of galena or sulphide of lead. This is inserted as a shunt on a condenser placed in the receiving circuit, and in series with the detector is inserted the signal producing instrument, which may be a double telephone worn on the head of the operator. A coherer detector associated with a relay and Morse printer can also be employed if necessary. Above the receiving table is seen the switch throwing over the antenna from the transmitter to the receiver.

As an example of a station combining in one the spark and the arc methods, we may take that at Cullercoats, on the Northumberland coast, about eight miles from Newcastle, England, erected by the Amalgamated Radiotelegraphic Company. The station itself is situated on a promontory running out to sea. It comprises a small four-roomed, one-storied building, and a large umbrella antenna supported by a single wooden lattice tower (see Fig. 15). The mast is built up of baulks of timber 6 inches square, jointed in lengths. It is 220 feet high and 2 feet square at the base, and supported in a foundation of concrete and stayed by wire ropes cut up into lengths by insulators of creosoted wood. The antenna is constructed of bronze wires (see Fig. 16) which extend from the top of the mast and

spread over a circle of 220 feet in diameter. It is made in two parts, each consisting of twelve wires, and stretched out into a wide semicircle by guy ropes attached to anchors fastened to various rocks. The twenty-four wires of the complete antenna are connected at their lower ends to one wire which encircles the mast at a height of about 100

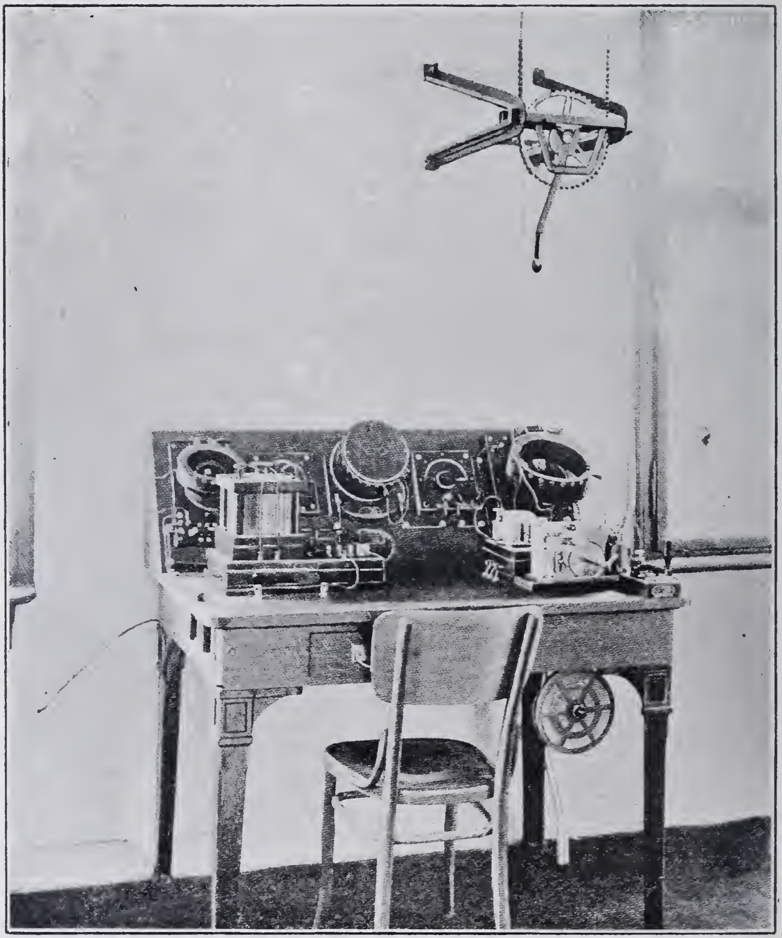

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FIG. 14.—Receiving Apparatus and Desk in Nauen Station.

feet. The upper ends of the two halves are connected to two cables which come down into the station building. It will thus be seen that if the two cables are not connected together, the wires form a loop antenna, but if they are connected together they form a single antenna. The earth plate at the station consists of a large number

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FIG. 15.

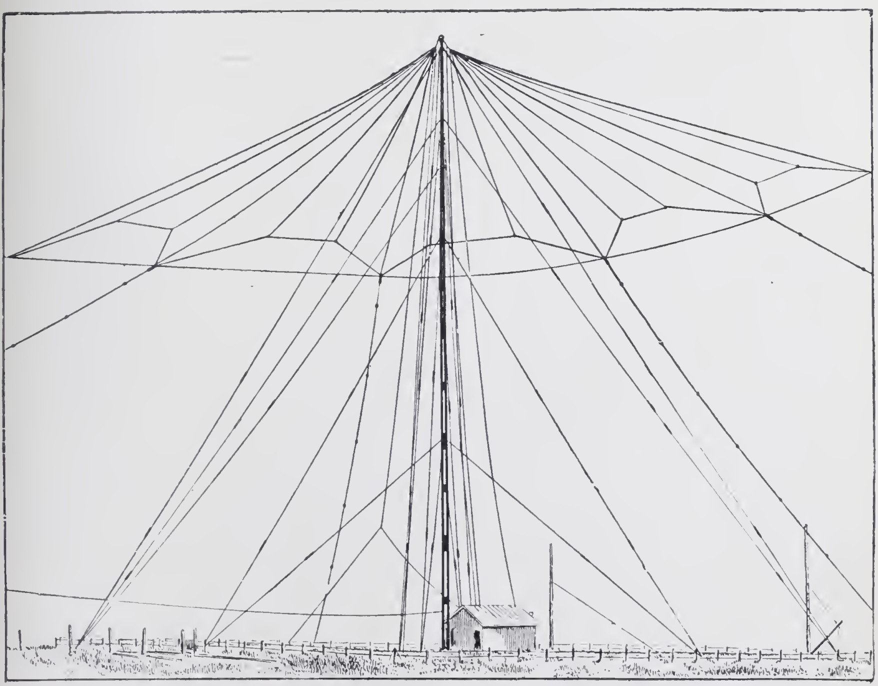

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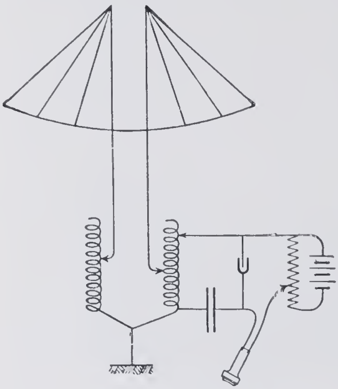
FIG. 16.

of wires buried about two feet in the ground radiating in all directions from a point near the foot of the mast. The station contains both spark and arc apparatus. In the case of the spark apparatus the power is supplied by an 8-h.p. motor driven directly from the town electric supply, and is coupled to a 5-k.w. alternator supplying 14 amperes at 400 volts, and at a frequency of 120. This alternating current is raised by a high tension transformer to 50,000 volts. The sending operator can start and stop the alternator by a switch from the operating table. The primary current of the transformer passes through a sending key to interrupt it in accordance with the signals of the Morse alphabet. The high tension alternating current is led to a third room in which there is a large battery of Leyden jars and an associated inductance and spark gap, forming the oscillatory circuit. This inductance is directly connected to the antenna through a large switch, which changes over the antenna from the transmitting to the receiving system when receiving. There are the usual tuning coils inserted in the circuit of the antenna. The reception is conducted by means of an electrolytic oscillation detector and a telephone, the antenna being arranged as a loop antenna (see Fig. 17). With this apparatus communication is carried on for about 400 miles between Cullercoats and Christiana.



[*From "The Electrician."*

FIG. 17.

The station also contains a Poulsen arc apparatus. The arc generator consists of a metal box with marble ends, shown at the left-hand bottom corner of Fig. 18. This box contains the copper and carbon electrodes, the cooling of the copper anode and the arc box being effected by radiating flanges exposed to the air and not by water circulation (see Fig. 19). The striking of the arc is accomplished by lifting the copper electrode momentarily by a lever and then allowing it to fall to an adjusted distance. The box is kept full of hydrogen supplied from a gas cylinder or from a calcium hydride generator, by which hydrogen is generated by dropping calcium hydride into water. About two pounds of hydride provide enough hydrogen for 60 hours' continuous work. In some cases coal gas is used instead of hydrogen.

The carbon cathode is rotated by clockwork. The usual telegraphic work is carried on with a single copper-carbon arc having a fine adjustment for arc length, the arc being formed in a strong magnetic field perpendicular to it. The windings of the electromagnet are in series with the arc as well as with a variable resistance, and the arc is formed by a continuous current of 480 volts taking 10 or 12 amperes. The oscillation circuit is arranged as a shunt to the arc with a direct connection to the antenna. This circuit comprises an inductance coil of many turns, and a condenser formed of zinc plates immersed in oil. The plates are separated by

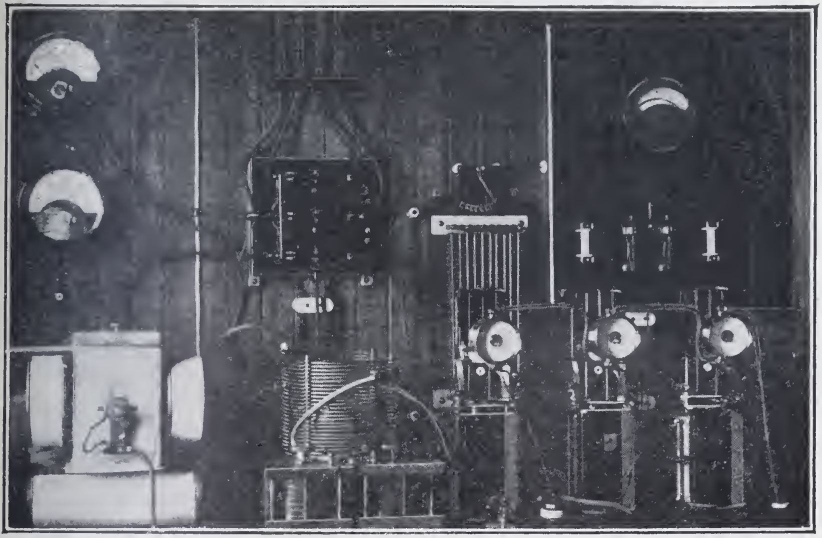


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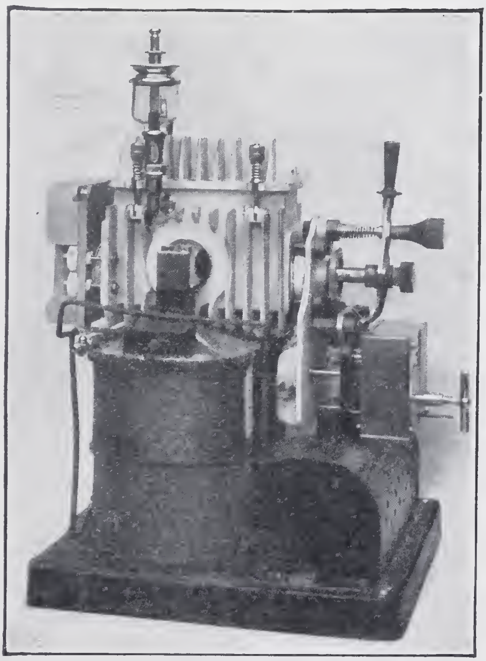
FIG. 18.—Poulsen Arc Apparatus in Cullercoats Station.

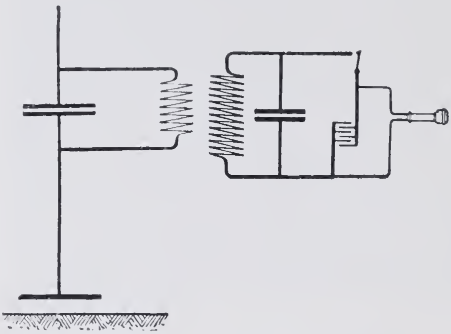


[*By permission of the Amalgamated Radiotelegraphic Co., Ltd.*

FIG. 19.—Poulsen Arc Apparatus.

a distance of 3 mms., and the capacity is arranged in two sections, so that, although a point on the inductance coil is put to earth, the terminals of the arc remain insulated. A variable condenser is connected in parallel with the fixed condenser to enable changes to be made in the emitted wave length, which is usually between 1200 and 1500 metres. A hot wire ammeter is inserted in the earth connection to show the current passing into the antenna.

The signalling is effected by short circuiting a few turns of the inductance coil, and therefore altering the wave length of the emitted waves. The frequency employed is about 200,000, and the current into the antenna about 10 amperes. The receiving apparatus used with these undamped waves consists of an oscillation transformer of which the two circuits are very loosely coupled, the primary being joined to the terminals of a condenser inserted in the antenna circuit, and the secondary connected to another large condenser, and also intermittently to a telephone shunted by a third condenser (see Fig. 20).



[*From "The Electrician."*

FIG. 20.

The connection between the telephone and the condenser circuit is made by means of a *ticker*, or vibrating electromagnetic-worked contact, in which a very light, rapidly moving hammer closes and opens the circuit. When the circuit is open, energy accumulates in the large condenser, and on closing it some of it passes into the condenser of the circuit, and on the opening of the contact again this condenser discharges through the telephone. The contact points of the ticker are made of crossed gold wires, and the vibrating mechanism is enclosed in a small sound-proof box. The observer, therefore, hears as sounds of longer or shorter duration in the telephone the more or less prolonged short-circuiting by the sending key of part of the inductance in the transmitting circuit. Owing to the loose coupling, the tuning is very sharp, and it is easy to perceive in this receiver the effect of altering about one-half per cent. in the capacity of the sending circuit.

The advantages claimed for the arc method of signalling are first its silence, and, secondly, the entire absence of sparking at the sending key, also the greater compactness of the apparatus and the lower voltages dealt with. For example, the maximum potentials which occur at the top of the antenna when the undamped waves are being used are probably not greater than 2000 or 3000 volts, and the insulation required in the apparatus itself is only for voltages of the order of 1000 volts. It is also affirmed that atmospheric disturbances are much less felt when using the undamped wave apparatus than when using the damped waves. Furthermore, it is claimed that comparative tests of the arc and spark methods, carried out over ranges of

about 900 miles, have shown that the undamped waves are less obstructed by mountainous country than are the damped waves of a spark transmitter of the same wave-length when using about the same sending power. Up to the present time, however, the arc method of generating undamped oscillations has not passed beyond the experimental stage, and it remains to be seen, therefore, whether in practical working these differences will give rise to any marked advantage.

6. Methods for Simultaneous Transmission and Reception of Messages.—The convenience and economy of time resulting from the power to send and receive messages simultaneously between a pair of stations has attracted the attention of inventors, and numerous schemes have been proposed or tried.

In the ordinary method of working usual at present the operator at any one station uses the same antenna for both sending and receiving alternately. He switches this antenna on to the transmitting or receiving apparatus at pleasure to send or to receive. There is, however, always the difficulty that he may be trying to send at the same moment that his distant correspondent is sending to him, and hence confusion results. Accordingly, operators have to be careful to wait upon one another, and not to interrupt or change from receiving to sending or *vice versâ* without notice duly given.

The basis of all methods so far devised for simultaneous reception and transmission is to employ some mechanism for switching the antenna over rapidly and for short intervals from the transmitter to the receiver. The operator thus endeavouring to send a *dash* signal has not the antenna at his disposal for so doing continuously, but for a series of short fractions of a second in between which it is connected to his receiver, and he is then in a position to receive. In order that this process may be successful, some means has to be contrived for preventing clashing. That is to say, if there are two stations A and B in correspondence, the station A must be in a condition to receive when B is sending, and in a condition to send when B is connected for reception.

Many inventors, therefore, have endeavoured to devise synchronized mechanism which shall keep the stations in the above-mentioned alignment and correspondence. Any such mechanism is, however, extremely liable to get out of step, and to fail in its purpose.

As the author does not know of any successful practical application of such synchronizing mechanism, it is unnecessary to describe in detail any of the numerous plans proposed in patent specifications, but which have probably never been put into practice. Some methods have been devised which do not depend upon synchronization of revolving commutators at distant stations, but are of somewhat doubtful practicability.

One method was patented by J. S. Stone in 1901 (see U.S.A. Patent No. 716,136, applied for January 23, 1901). In his specification the patentee proposes to employ two sending antennæ in which oscillations in opposite phases are excited. At a point midway between them a receiving antenna is set up, which will be influenced by arriving waves, but which will not, therefore, be affected by the opposed oscillations in the two local sending antennæ. These last

the patentee says, should preferably be placed half a wave length apart. This, however, is quite impracticable in the case of the wave lengths now generally employed. Also such a pair of antennæ would constitute a directive system, and radiate chiefly in the plane of the antennæ, and not at all in a direction at right angles. Hence, on these grounds the plan can hardly be considered a satisfactory solution of the problem.

Lee de Forest, in a U.S.A. Patent, No. 772,879, applied for June 4, 1903, proposes another method which consists in inserting in the receiving circuit a revolving commutator which opens that circuit periodically. This commutator is driven by the alternator or interruptor which creates the spark discharges in the transmitter circuit, and is so arranged that the receiver circuit is to be open when the transmitter spark occurs, but is to be closed in the intervals between. Hence, when the sending operator closes the key to make a signal consisting of one or more spark discharges, his own receiving circuit is only closed at intervals between the sparks he is creating, and at those times can receive signals from a distant station.

By employing different spark frequencies at the two stations in correspondence, the chances of the sparks occurring at the two stations simultaneously are reduced to a very small amount. The assumption, however, which lies at the base of the proposal is that the spark intervals are perfectly regular. By the employment of the author's spark counter it can be shown that this may not be the case, and that an irregularity in spark intervals occurs even if the alternator frequency is constant.

A somewhat similar plan was proposed by R. A. Fessenden (see U.S.A. Patent, No. 793,652, applied for April 6, 1905).

The successful performance of simultaneous reception and transmission or duplex radiotelegraphy requires something more than means for switching the antenna over rapidly and alternately from the receiving to the sending apparatus, and it must dispense with any need for synchronization between commutators in distant stations if it is to be thoroughly practical.

Mr. Marconi clearly recognized this fact, and has devised a plan for use in conjunction with his own rotating dischargers, which essentially depends on the fact that if the periods during which any one station is in a condition to receive are long compared with the time during which it is in a condition to send, no synchronization is necessary. This can be explained as follows: Let the long black lines in Fig. 21 represent the time intervals during which Station A has its receiving apparatus connected to the antenna, and the short spaces between these lines the time intervals during which the same antenna is in connection with the transmitter at Station A. Thus, if the last-named intervals are each 0·001 of a second, the longer intervals for reception may be 0·01 of a second.

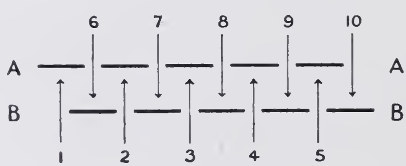


Fig. 21.

These periods for reception and transmission are made to succeed each other very rapidly and uniformly.

Suppose, then, at the Station B a similar series of intervals of reception and transmission is taking place, during which the antenna at B is in connection with the receiving and sending apparatus respectively. These intervals at B may be following each other rather more quickly than those at A. We may represent this difference by supposing the interrupted line marked B in Fig. 21 to slide past the interrupted line marked A. It is clear, then, that at certain intervals of time, and for very short instants, the stations A and B will both be sending at the same instant; but if the periods of time during which they are each in a condition to receive are long compared with the time during which they can each send, the result will be that each station will, on the whole, for the greater part of the time, find the other in a receptive condition when it is sending.

Mr. Marconi's arrangement is specially adapted for use with his high-speed rotating disc discharger with studs on the disc in which short spark discharges occur at very frequent intervals, with much longer intervals between them. The method consists in using for reception all the idle intervals between the times at which sparks occur when the studs pass between the polar discs.[1] This is accomplished by rotating one or more commutators synchronously with the studded disc. These commutators consist of insulated wheels or discs C_1, C_2 having metal plates let into them and also brushes B_1, B_2 pressing against these plates (see Fig. 22) in such a manner that the brushes are short-circuited and an electric circuit closed at certain intervals during the time of rotation. In the diagram in Fig. 22 two separate antennæ (RA, TA) are shown for the sake of explanation, but it must be understood that in practice these may be one and the same. One of these, TA, is shown in connection with the condenser circuit which includes the rotating discharger, and the other, RA, is shown in connection with the receiver. If the key in the circuit of the exciting transformers is depressed for long or short periods, a series of discharges will take place across the gaps between the side wheels of the discharger SD_1, SD_2, and the rotating disc, D, carrying the studs. It will be seen from the diagram that the receiving aerial is disconnected from the receiving apparatus, and that the receiving apparatus itself is short-circuited whenever a stud of the rotating disc is in the discharge position. The sending operator, therefore, so to speak, has the antenna in his possession for short periods of time at regular intervals, and if he depresses the key, making either a dash or a dot, a greater or less number of studs will pass the gap accompanied by discharges during that time. Thus, for instance, he makes a dot by depressing the key for a short time, then three or four studs may pass the gap in that time; but if he presses the key for a long time, making a dash, a dozen or more studs may pass, each passage of a stud being accompanied by a train of oscillations from the reservoir condenser. During the time that these oscillations are taking place the antenna is, as described, disconnected from the receiving apparatus, but in the intervals between the passage of the studs it is

[1] See Marconi's British Patent Specification, No. 16,546, of 1908.

connected, and is therefore in a condition to receive signals from the distant sending station. It is necessary, however, to make sure that there is a certain correspondence between the two stations in this respect, viz. that whilst one station is sending the other must be in a condition to receive, and *vice versâ*. As already explained, this can be achieved without any means of synchronizing the dischargers at both stations in correspondence, provided that the operative periods of the sending apparatus are much shorter than those of the receiving apparatus. In other words, at any one period during which the antenna is connected to the receiver must be much longer than the period during which it is connected to the discharger. Hence,

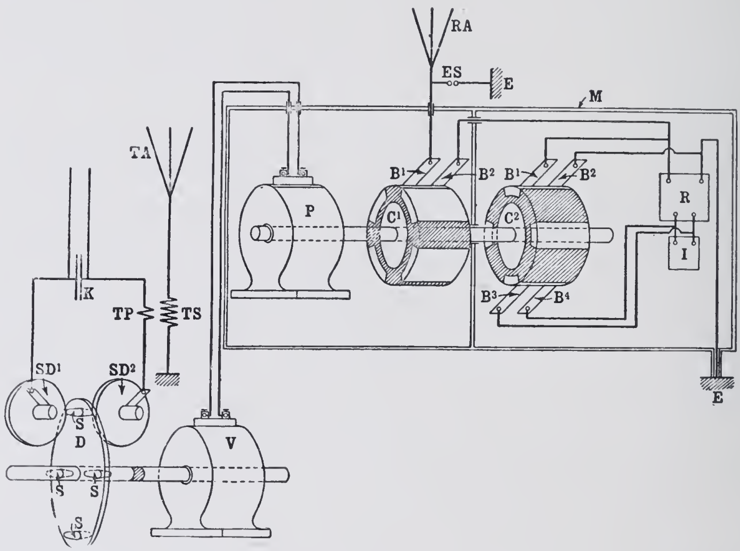


FIG. 22.—Marconi's Apparatus for simultaneously sending and receiving Radiotelegraphic Messages. V, P, electric motors coupled electrically or mechanically so as to run synchronously; D, Marconi studded disc discharger; C_1, C_2, commutators; B_1, B_2, B_3, B_4, brushes; R, receiving instruments, I, indicating instrument; TP, TS, transmitting jigger, which in actual practice is inserted in the antenna RA, just above the short spark gap ES; the receiving instrument RI is short circuited at the moment when a discharge is taking place at the studs S.

if a dot signal arrives to be received, a very short fraction of it may be lost owing to the operator at that station sending during certain fractions of the time represented by that dot signal, but enough will be received to record an audible dot signal in the telephone or other receiver. There is, therefore, no necessity for any synchronization of the dischargers at distant stations. In fact, they must not rotate at the same speed, and the chances of their so doing and falling exactly into step is very small. Accordingly, by this ingenious plan Mr. Marconi evades all necessity for elaborate devices for synchronization, which, however well they look on paper, are not at all likely to give satisfaction in actual work.

Another method which requires no synchronization of commutators at distant stations is that proposed by F. Van der Woude, patented in England by the Amalgamated Radiotelegraphic Company,[2] and described in the specification as below, although the author is not aware that it has ever been put into practice. It comprises a rapidly rotating contact maker (see Fig. 23) which performs the following sequence of operations rapidly and in the order named:—

(*a*) The transmitter is connected to the antenna for a very short period.
(*b*) The antenna is connected also to earth.
(*c*) The transmitter is disconnected from the antenna.

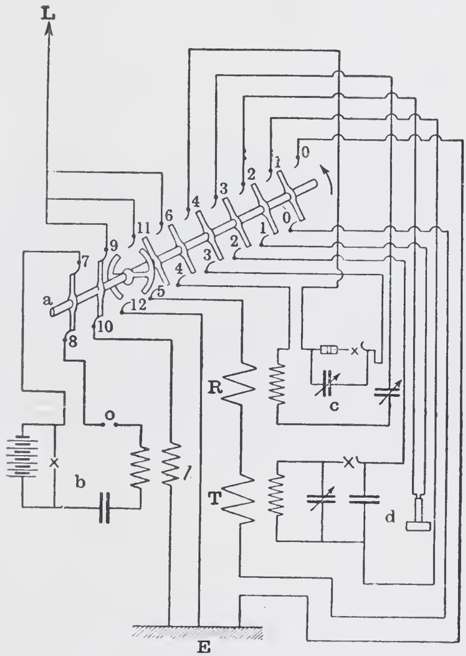


Fig. 23.

(*d*) The receiver is connected to the antenna.
(*e*) The earth connection is removed.
(*f*) The receiver is disconnected from the antenna.

The condition of success is that the shaft *a* (see Fig. 23), which drives the commutator carrying out the above-mentioned operation, should make one complete cycle or revolution at least during the time occupied by a telegraphic *dot* signal. Another condition is that the commutators at corresponding stations should *not* be in synchronism. The first condition is easily satisfied, and the result is that the operator can always receive and always send a dot signal during the interval of time occupied by one revolution of the commutator, and therefore also send a *dash* or receive a *dash* at any time.

[2] See British Patent Specification, No. 6953, of 1908.

7. Tuning and Interference Prevention.—We have already discussed the problem of the isolation of radiotelegraphic stations and some of the methods which are adopted for preventing the signals sent out by any one station from affecting the receivers of other stations for which they are not intended. In the present section practical methods for effecting this isolation will be considered.

As already mentioned, the greater part of the successful work in connection with radiotelegraphic privacy is based upon the facts of electric resonance. If there are two sending stations, A and B, and a third station, C, which can receive from either of the two, then within certain practical limits, the station C can pick up the signals either from A or B by the process of tuning to the wave-length of the station from which messages which it is desired to receive come, provided these waves are different. From the explanations given in Chaps. III. and VI., it will be evident that this depends upon the form of the resonance curve proper to the station C when in correspondence with either of the stations. If we suppose the station C to have a receiver which is metrical, such as a hot wire barretter or thermal ammeter, the indications of which are proportional to the R.M.S. value of the oscillations in the detector circuit, then if the wave-length of the incident waves is progressively altered from some low value to another one much higher, the current as measured by the metrical detector in the receiving circuit of the station C will gradually rise to a maximum and fall off again ; the curve delineated when the R.M.S. value of this current is set off in terms of the wave length or frequency of the incident waves is called a resonance curve. Or, otherwise, assuming the wave-length of the incident waves to be constant, the proper frequency of the receiving apparatus may be progressively altered from a value much below to a value much above the frequency of the incident waves, and a resonance curve plotted in terms of this proper frequency of the receiving instrument. This resonance curve, as explained in Chap. III., will depend upon the decrement or damping of the receiving apparatus and also that of the transmitting apparatus or incident wave trains. If the receiving apparatus has a very small decrement, and if the incident waves are slightly damped, a very small variation in the proper frequency of the receiving apparatus will cause the current in it to fall very much in value, and if in place of a hot wire ammeter, some detector, such as an electrolytic detector or magnetic detector, is employed with a telephone as a signal-producing instrument, then a very small variation in the proper frequency of the receiving circuits may cause the current in them to fall so much that the telephone no longer gives an audible sound. In this way the incident waves are said to be "tuned out." Accordingly, if there are two stations, A and B, sending out waves of different wave-lengths, the operator at the station C has it in his power to tune out either of these two stations and confine his reception to that of the other one. With proper appliances, and if the resonance curves are sharp, this can be done if the wave lengths differ by only 1 or 2 per cent., or perhaps less. If, however, the stations A and B are very near to the station C, or if one of them, A, is very near, and B is far off, then it will be much

more difficult, and perhaps impossible, for the station C to tune out the communications from the near station whilst receiving those from the more distant station. It is well known, however, that if the receiving circuits in the station C consist of an antenna which is inductively coupled to a closed receiver circuit comprising a capacity and an inductance, then if the coupling between the antenna and the receiver circuit is very loose, it will be much more easy to tune out a station not too near than if the circuits are closely coupled. In radiotelegraphic language, the tuning will be more sharp. Similarly, it has been found that if an antenna circuit is inductively coupled with a closed intermediate circuit comprising a capacity and inductance, and if this intermediate circuit is inductively coupled with another closed circuit containing a receiver, and if all three circuits are put in resonance with the received wave, and if the coupling is made loose in the case of all three circuits, then the receiver will be still more free from interference by waves

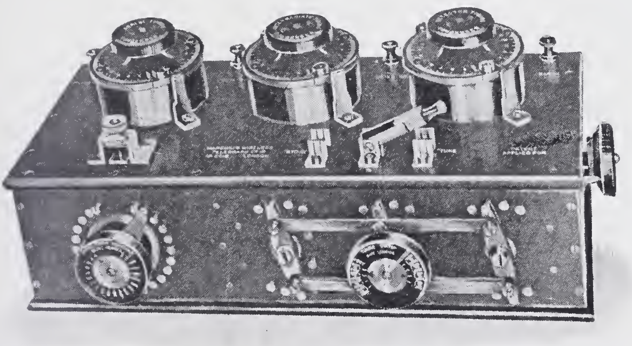


Fig. 24.—Perspective View of the Marconi Tuner.

differing slightly in wave length from the wave length proper to the tuning. Increasing the number of inductively coupled circuits and decreasing the coupling between the circuits increases the freedom of the receiver from interference by non-syntonic waves, but at the same time decreases the strength of the signals in the receiver. Based on this principle, the Marconi Company have devised a "tuner,"[3] or instrument intended to put this principle into practice with expedition and certainty.

This Marconi tuner consists of a box which is provided with three adjustable condensers and five adjustable inductance coils (see Fig. 24). These condensers consist of semicircular metal plates separated by some dielectric such as ebonite, alternate metal plates being connected together to an axis, so that by rotating this axis one set of plates can be more or less moved in between the others, and the capacity of the condenser so formed varied, the actual capacity being indicated by a divided scale on the head. This instrument

[3] See British Patent Specification, No. 12,960, June 4, 1907, granted to the Marconi Wireless Telegraph Company, Ltd., and C. S. Franklin.

contains three such condensers, respectively called the aerial tuning condenser, the intermediate tuning condenser, and the detector tuning condenser, and these condensers are arranged in connection with inductance coils as shown in Figs. 25 and 26. In this diagram, A (Fig. 25) represents the antenna or aerial wire, and B represents an aerial tuning inductance in series with it, and C_1 represents the aerial tuning condenser, and in the same circuit is inserted any desired portion of another coil P_1, one point of which can be put to earth E. The coil P_1 is loosely coupled with another coil S_1, which forms part of the intermediate circuit comprising the intermediate condenser C_2 and the two coils S_1 and S_2; S_1 being loosely coupled with the coil P_1, and S_2 loosely coupled with the coil P_2, which last coil, together with the condenser C_3, called the detector tuning condenser, forms the circuit to which the receiver R is connected, which may be the coil of a magnetic detector or of any other suitable receiver. The oscillations set up in the antenna A set up oscillations in the coil

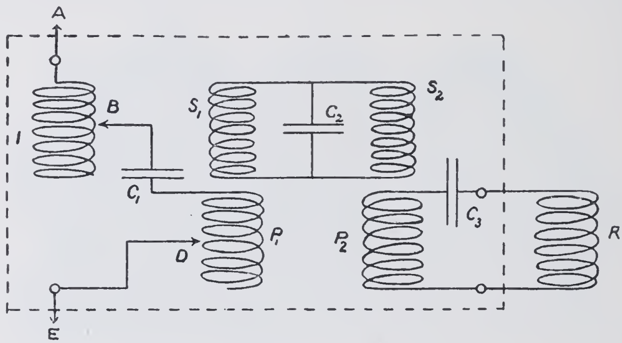


FIG. 25.—Circuits of the Marconi Tuner.

P_1, which induce others in the coil S_1, and these again other oscillations in the coil S_2, and these in turn set up oscillations in the coil P_2 which finally affect the receiver. The coupling of the coils S_1 and P_1 can be altered, and also of S_2 and P_2, and the inductances and capacities are also variable, as described. The capacity of the condensers C_1, C_2, and C_3 can be continuously varied from zero to a maximum value of about 0·001 microfarad.

In adjusting the instrument for use, the antenna circuït, comprising the coil B and the condenser C_1 and a portion of the coil P_1, has to be varied until its natural period coincides with that of the waves to be received. The intermediate circuit, comprising the condenser C_2 and the coils S_1 and S_2, has then also to be tuned by varying the capacity until it has the same period, and in like manner the circuit containing the coil P_2 and the condenser C_3 has to be tuned until it has the same natural period. Looking at the perspective view of the instrument (see Fig. 24), the aerial condenser is the left-hand condenser, the intermediate condenser is the middle condenser, and the detector condenser is the right-hand condenser. The handles of the aerial tuning inductance and of the tuning switch are in the front of the instrument, and the handle of the intensifier is at the right-hand side of the instrument.

This instrument is mostly employed by the Marconi Company in connection with the Marconi magnetic detector. Hence there are four terminals on the instrument respectively marked *earth*, *aerial*, and *magnetic detector*. The aerial or antenna is generally connected with the earth terminal through a plunger switch, so that the tuner is disconnected from the antenna when transmitting. In setting the aerial tuning inductance and aerial condenser, the best values to select, of course, depend upon the wave length to be received. A little experience shows which are the best values to use at any particular station, but the following is the process for adjusting the

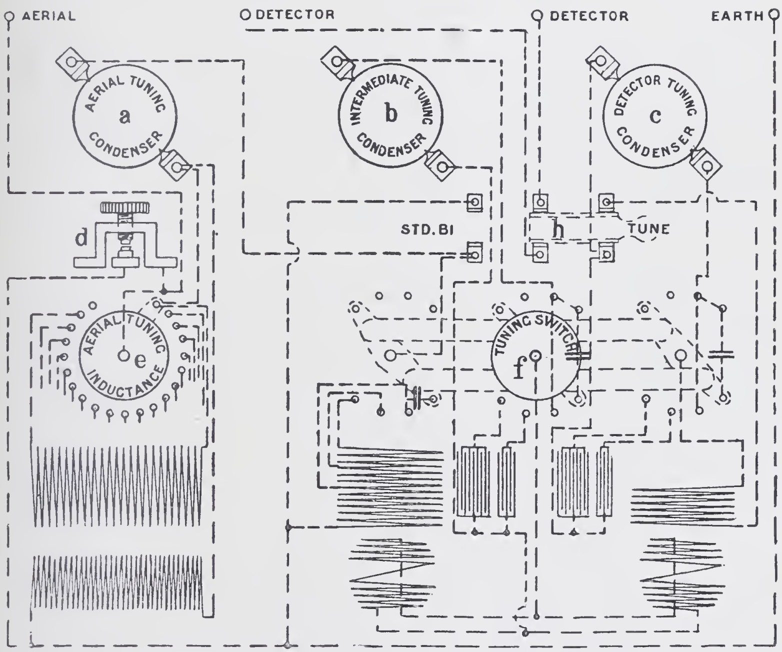


FIG. 26.—Details of the Connections of the Marconi Tuner.

instrument when signals from the station with which it is required to communicate are to be picked up.

1. Adjust the aerial tuning inductance, keeping the aerial condenser short-circuited, and then the aerial condenser must be adjusted until the strongest signals are obtained.

2. Set the intensifier handle to 90°.

3. Set the tuning switch to the wave length roughly indicated by the amount of the aerial tuning inductance and the aerial condenser.

4. Throw over the changing switch to tune, and then vary the intermediate tuning condenser and the detector tuning condenser together until the best signals are obtained. It is necessary that these two condensers should be varied as nearly as possible together.

5. Adjust the aerial tuning condenser to give the strongest signals,

and if any interference is found adjust the intensifier to a small value, and then adjust the condensers again. The further this intensifier handle is turned from 90° the sharper will the adjustments of the condensers become, owing to the looser coupling and the greater freedom from interference.

Other radiotelegraphists, such as R. A. Fessenden, have endeavoured to mitigate the evils of unintentional or intentional disturbance by inventing various forms of receiving circuits, the object of which is to assist the operation of resonance in rendering a receiving station immune from the influence of any incident electric waves other than those which it is desired it should receive. One method Fessenden has adopted with success he calls his *Interference Preventer*.[4]

Suppose three antennæ to be erected at a receiving station, which will be called A_0, A_1, and A_2. Let receiving circuits be connected with each of these, each actuating some oscillation detecting device, such as a barretter, which in turn produces a signal by means of a telephone. A telephone is provided having four coils on it, which will be denoted by C_0, C_0, C_1, and C_2.

The coils C_1 and C_2 are in connection with the circuits of antennæ A_1 and A_2, and the two coils C_0 and C_0 are in connection with the receiver attached to the antenna A_0.

The antenna A_0 and its associated circuits are tuned to the wave length it is desired to receive, and the antenna A_1 to a frequency slightly above that frequency, and the antenna A_2 to a frequency slightly below. The coils C_1 and C_2 are so wound on the telephone magnet that they oppose the action of the coils C_0 and C_0, which latter are joined in series. Suppose, then, that a wave falls on the antenna which is not in tune with any of them. It will create forced oscillations in the receiving circuits, but the currents due to the oscillations in A_1 and A_2 will oppose those in A_0, and as far as the telephone is concerned, the action will nearly neutralize each other, and no sound will be produced. If, however, a wave of exactly the right frequency is incident, viz. that for which the antenna A_0 is tuned, then although some forced oscillations may be set up in A_1 and A_2, yet the actions due to A_0 will preponderate, and the telephone will give an audible signal. In practice three separate antennæ are not used, but three receiving sets properly tuned are attached to one single antenna, which then becomes far less responsive to vagrant waves than it would be if dependent upon selective power or upon pure resonance alone.

There can be no doubt that for stations in close contiguity some self-protective device of the above kind is needed. When using oscillation detectors of the potential actuated type, such as the coherer, the amount of immunity from undesired influence which can be secured even by careful syntonization of the circuits is not sufficiently large to meet the requirements of commercial work. Hence the preference given of later years to current-actuated receivers like the magnetic detector, and to quantitative receivers such as the

[4] See *The Electrician*, vol. 61, p. 221, 1908; also *Science Abstracts*, vol. 11. B., 1908, *abs.* 198. Also R. A. Fessenden, British Patent Specification, No. 4709, of 1907. Fig. 2.

electrolytic detector, or the author's oscillation valve or glow lamp detector.

Availing himself of the last-named receiver, Mr. Marconi has invented a form of receiving circuit which is highly immune from disturbance by waves of large damping or by non-syntonic waves. The description, taken from his British Patent Specification, No. 4125, of 1909, is as follows:—

The object of this invention is to provide an improved wireless telegraph receiver from which the disturbing effects due to atmospheric electricity or to electrical waves of a period or decrement different from that of the transmitter from which it is desired to receive shall be eliminated.

In a prior specification, No. 887, of 1907, he described a method of utilizing the author's glow lamp detector or oscillation valve in a wireless receiver, and the present invention relates to the more effective employment of these valves and similar detectors which act by reason of their property of rectifying electrical oscillations.

According to this invention two rectifying detectors or valves are connected respectively to the secondaries of two oscillation transformers or jiggers, the primaries of which are joined to the receiving aerial or elevated conductor.

A condenser is inserted in the circuit of each of said secondaries, and these two circuits are arranged in such a manner that one of them is in resonance with the electrical waves which it is desired to receive, while the other is slightly out of resonance, or, in other words, has a period differing slightly from that of the said waves. The valves are so connected to an induction coil, telephone, or other detector that the rectified currents which they generate in consequence of the received oscillations are opposed to each other in polarity.

As a practical guide to putting the invention into practice, we subjoin the arrangements which we find work best.

Figs. 27 and 28 are diagrams of two arrangements of the receiving circuits which have been successfully employed.

In Fig. 27 S and S_1 represent the secondaries of the oscillation transformers or jiggers, of which the primaries P and P_1 are in the aerial circuit, V and V_1 are the Fleming valves or rectifiers, B and B_1 the batteries for rendering the valve filaments incandescent, K and K_1 are two condensers of equal capacity inserted in series with the secondary of the telephone transformer T, the primary of which is connected to a telephone or indicator D. Across the condensers K and K_1, the capacity of which should be about 0·003 microfarad, it is advantageous to place two high resistances L and L_1 of about 40 megohms.

In Fig. 28 an arrangement is shown in which the condensers K and K_1 and the resistances L and L_1 are omitted, but variable resistances or potentiometers R and R_1 are inserted across the terminals of the valves and batteries, the connections to the telephone transformer T being tapped off at points close to the negative poles of the valves, the best points being easily ascertained by a process of trial and error by means of sliding contacts.

In order to properly balance the effect of the two valves, further

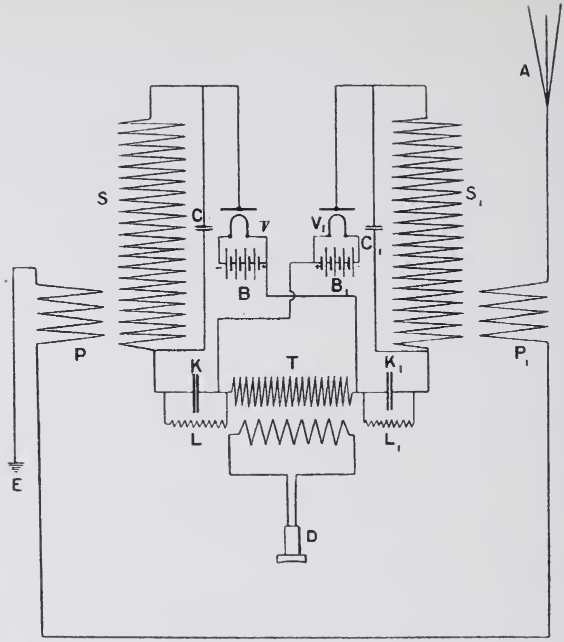


FIG. 27.—Marconi Receiving Circuit, arranged to be immune from Atmospheric Disturbances.

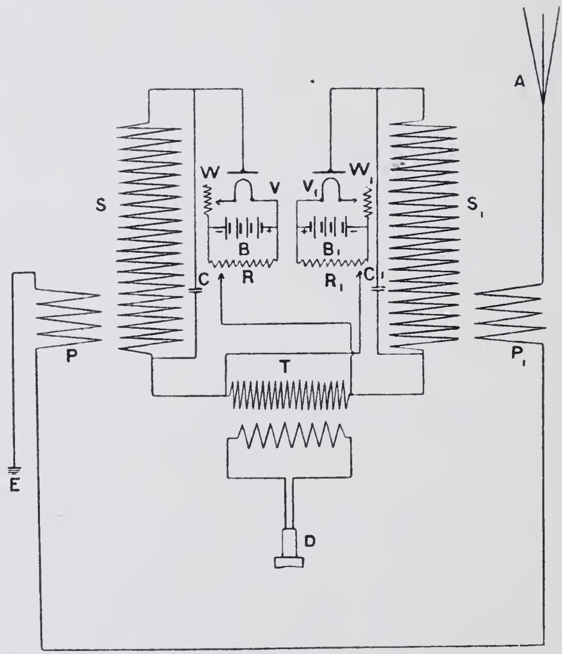


FIG. 28.—Marconi Receiving Circuit arranged to be immune from Atmospheric Disturbances.

adjustable resistances W and W_1 may be placed in series with the filaments.

By this method it is possible by the adjustment of the condensers C and C_1, or by variations in the couplings between the aerial and the oscillation transformer circuits, to so balance against each other the impulses produced by both valves in consequence of disturbing influences that these impulses are neutralized, and therefore cease to interfere with the reception of signals, which is effected through that valve circuit which is arranged to be in resonance with the periodicity of the electric waves which it is desired to receive.

8. The Effect of Obstacles and of Atmospheric Conditions between the Sending and Receiving Antennæ.—Although earlier observations seemed to show that hills, trees, and buildings did not form an insuperable barrier to telegraphic communication by electric waves, yet later quantitative measurements have proved that the effects produced by the interposition of such obstacles is quite sensible, and in some cases very pronounced.

The diminution of signalling distance due to the interposition of hills and cliffs of various materials and heights has been carefully investigated by Admiral Sir Henry Jackson, of the British Navy, and his results were communicated to the Royal Society of London in 1902.[5]

The experiments were conducted between ships of the British Navy provided with apparatus on the Marconi system, the cymoscope used being a metallic filings coherer, and the test employed being the maximum distance at which good Morse signals could be sent between two ships. The transmitting and receiving apparatus were timed, and the wave length employed was the fundamental one used in the British Navy. The wave length used is not precisely stated in the paper, but was probably 500 or 1000 feet. In describing the results, we shall quote freely from Admiral Jackson's paper. The observations proved that the interposition of land, especially rocks of certain kind, greatly reduces the maximum signalling distance between ships equipped with wireless telegraph apparatus as compared with the distance over open sea for the same equipment. The results are collected in the tables on pp. 814 and 815. These tables, III. and IV., and accompanying diagrams 1 to 8 given in Plate VII. (see p. 816), are, by kind permission, taken from Admiral Jackson's paper.

In reference to the above observations, Admiral Jackson says—

"An examination of these results shows the marked difference between the effects due to the various natures of the intervening land.

"Summarizing them for soft rocks, hard limestone, and limestone containing a large proportion of iron ores respectively, the percentage of maximum signalling distance through them compared to the open-sea distance is as follows:—

	Soft sandstone, shale, etc.	Hard limestone.	Iron ores.
Maximum distance	81	68	Less than 40
Minimum „	56	25	„ 23
Mean „	72	58	„ 32

"Consider, firstly, the soft rocks: The two maxima percentages of distance

[5] See Captain (now Admiral Sir) H. B. Jackson, R.N., F.R.S., "On some Phenomena affecting the Transmission of Electric Waves over the Surface of Sea and Earth," *Proc. Roy. Soc. Lond.*, 1902, vol. 70, p. 254.

TABLE III.

Observations by Admiral Sir Henry Jackson, on the Effect of Interposed Obstacles on Electric Wave Telegraphic Communication.

Reference number to fig. in Plate VII.	Height of aerial wire above sea.	Distance from the land.	Particulars of the land.				Height of aerial wire above sea	Maximum signal distance.		Percentage of maximum distance over land to over sea.
			Maximum height.	Total thickness.	Formation, strata, etc.	Surface.		At sea.	Over the land.	
	Feet.	Miles.	Feet.	Miles.			Feet.	Miles.	Miles.	
1*a*	158	2	150	4	Shale	Pasture, wet	178	62	50	81
1*b*	158	$1\frac{1}{4}$	250	7	Sandstone and slate . . .	Ditto	178	62	45	73
2	125	Yards. 130	200	$2\frac{1}{4}$	Porous sandstone	Building, dry	160	65	50	77
3*a*	125	250	250	6	Porous coral sandstone . .	Cultivated, wet . . .	160	25	20	80
3*b*	—	220	500	6	Ditto, over limestone . .	Ditto	—	—	17	68
3*c*	—	500	700	8	Ditto	Ditto	—	—	15	60
3*d*	—	1000	500	7	Ditto	Ditto	—	—	16	64
3*e*	160	Miles. 3	1083	6	Gritstone and marl . . .	Bare and dry, with scrub	125	—	17	68
3*f*	—	4	1400	9	Ditto	Ditto	—	—	14	56
3*g*	—	3	120	3	Semi-crystalline limestone.	Ditto	—	—	15	60
3*h*	—	1 to $2\frac{1}{2}$	5250	7	Ditto	Ditto	—	—	No signals	Very small
4*a*	160 + 500	On the land	500	Over 9	Porous sandstone	Cultivated, wet . . .	110	45	35	78 (T.)

The reference numbers in column 1 refer to the diagrams in Plate VII. at p. 816.

TABLE IV.

Reference number to fig. in Plate VII.	Height of aerial wire above sea.	Distance from the land.	Particulars of the land.				Height of aerial wire above sea.	Maximum signal distance.		Percentage of maximum distance over land to over sea.
			Maximum height.	Total thickness.	Formation, strata, etc.	Surface.		At sea.	Over the land.	
4*b*	Feet. 160 + 500	Miles. —	Feet. 600	Miles. Over 8	Porous sandstone, over limestone	Cultivated, wet . . .	Feet. 110	Miles. 45	Miles. 30, but none from 10 to 14	67 (T.)
4*c*	,,	—	400	22	Sandstone	Ditto	130	135	85 and over	Over 63
5	154 + 330	3	500	17	Limestone and iron ores .	Cultivated, wet and dry	125	105	40	39
6	125	Yards. 100	800	$\frac{1}{4}$	Ditto	Cultivated, wet . . .	110	45	None at 18	Less than 40 (T.)
7*a*	85	Miles. $3\frac{1}{2}$	834	$2\frac{3}{4}$	Limestone	Scrub and wood, wet .	55	20	10	50 (T.)
7*b*	85	3	432	$1\frac{3}{4}$	Limestone and much iron ore	Ditto, dry	55	20	None at 7	Less than 35 (T.)
7*c*	85	3	260	$1\frac{1}{2}$	Sandstone	Ditto	55	20	14	70 (T.)
8*a*	125	1	1800	22 16 plain	Limestone. Valleys between hills	Ditto, wet and dry . .	130	50	28	56
8*b*	125	2	1200	4	Limestone and iron ores .	Bare, wet and dry . .	160	65	15	23
8*c*	125	2	2060	6	Ditto	Ditto	160	65	None at 15	Less than 23

The reference numbers in column 1 refer to the diagrams in Plate VII. at p. 816.

(81 and 80) are over rather low land of no great thickness; the minimum, 56 per cent., is over high land, half as thick again as in these cases.

"Secondly, the limestone: The maximum percentage (68) is over the thinnest layer recorded of limestone (see 3*b* in Table III., p. 814, and corresponding diagram in Plate VII. opposite), the miminum (less than 25) is over a precipitous high mountain through which no signals could be passed at any distance, though they were obtained without difficulty over a low promontory of the same island and of the same formation, when both ships had moved to such positions as to bring the low instead of the high land between them (3*h* and 3*g*).

"Thirdly, the rocks containing iron ores: In all these cases a greater loss of proportional distance is recorded than in the others—and it was exceptional to receive any signals at all—and the best result recorded in several trials was but 39 per cent. of the open-sea distance.

"The results shown in Fig. 6 are the most conclusive that I have obtained in proving the screening effect of hard rocks containing iron ores on the passage of electric waves through land. The pinnacle of rock shown therein represents an extremely precipitous, narrow, but high promontory jutting out from the mainland and rising abruptly out of the sea, to which it is *steep to*, so that the ship could pass close to it in perfect safety at a distance of about 100 yards.

"To ascertain the effect of this wedge-like obstruction, the ship was steered close to the land, and her position was carefully noted when signals ceased or commenced. These signals were being sent continuously from another vessel (distant 18 miles) during the whole period of the trials, the letter F (- - ——— -, in Morse Code) being made by her at the rate of twenty-five per minute by my syntonic transmitter.

"The results showed that the signals ceased and commenced abruptly at the moment that the aerial wire passed the tangent from the transmitting ship to the edge of the cliff; the action was so abrupt, that, on one transit, the latter part of the long sign in the 'F' was the first indication of signals that was received; and on another transit, in the opposite direction, the long of the 'F' was the last sign received, the short being dropped; these were unusual results, as the signals generally die away gradually, the long signs breaking up, thus: (. . . . . .), and the shorts appearing as dots (.), before any signs are actually lost.

"Another point that may now be considered, is the case shown in (4*b*), when signals could not be exchanged when the ship was close under the land, but could be when clear of the land and in the same direction as before; the trial was repeated on several occasions for verification.

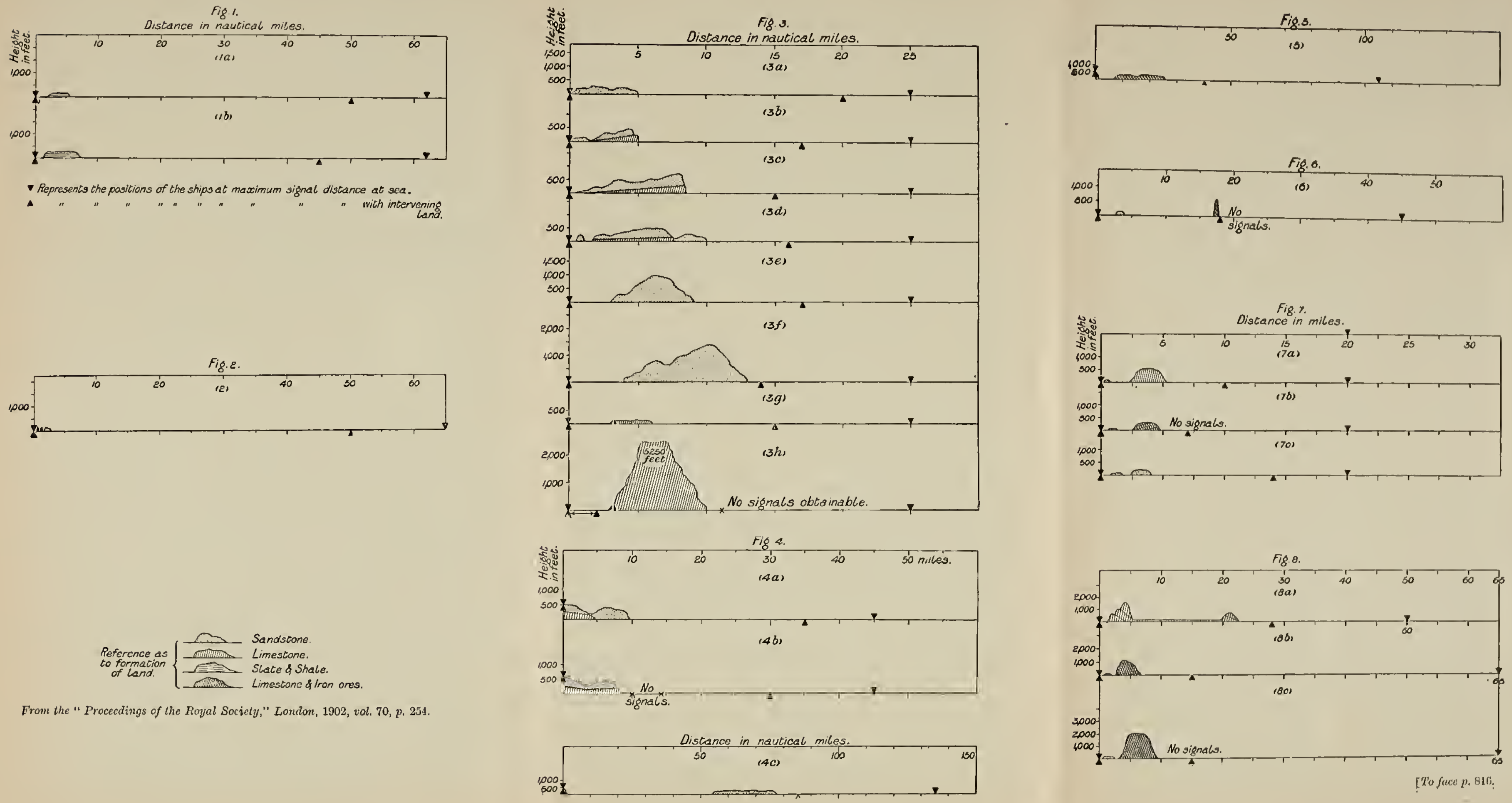
"Possibly the case previously considered is of the same class, as it is noteworthy, that when the ship was further off the promontory and also from the transmitting ship, though the two ships were still masked by high land of much greater thickness than before, a few stray signals were received occasionally, which evidently passed over, not round, and not through the land, as the ship was then in a land-locked bay.

"Referring now to 3*e* and 3*f*, where the intervening land was both higher and thicker, and yet did not stop signals at longer proportional distances, it may be concluded that the waves of electrical induction, which must pass from ship to ship in order to record signals, may in certain cases pass through the land. Thus: one of the ships was lying alongside a perpendicular cliff of considerable height, and yet only experienced a loss of distance of about 12 per cent.

"8*a* gives a typical case of waves passing through valleys, and the results were so marked and so frequently repeated with different ships and on separate occasions that eventually the track of a vessel, proceeding at a known speed, could be roughly estimated, though distant 25 miles, by noting the intervals between the times when signals were lost and when received, and comparing these intervals with the time taken by the ship to cover the distances between the valleys, which were well delineated on the chart, and through which the waves could evidently wind their way with less obstruction than by any other route.

"We have thus obtained evidence that the waves of electric induction may pass (1) through land, (2) over land, (3) round land, but that a large proportion of their energy is lost in doing so. (4) That the screening effect of the land varies with its nature, and is greater for iron ores than for limestone alone, and that for this latter it is greater than for soft rocks. No effects which could be attributed to interference of waves, due to reflection from a hilly background, have been recorded by me."

PLATE VII.—DIAGRAMS ILLUSTRATING THE RESULTS OF OBSERVATIONS BY ADMIRAL SIR HENRY JACKSON, R.N., F.R.S., ON THE EFFECT OF THE INTERPOSITION OF OBSTACLES ON TRANSMISSION OF SIGNALS BY ELECTRIC WAVE TELEGRAPHY.



From the "Proceedings of the Royal Society," London, 1902, vol. 70, p. 254.

[To face p. 816.

Admiral Jackson then describes his observations on the effects of varying conditions of the atmosphere on the effective distance working of electric wave telegraphy. He says—

"Some of these conditions constitute a most serious obstacle to the effective transmission of electric waves over medium distances, and are, in consequence, a source of error likely to be encountered, and which cannot be foretold nor allowed for in wireless telegraphy.

"These effects are much less frequently noticed in temperate than in subtropical regions. In the Mediterranean Basin they seem to be particularly prevalent, and most persistent in summer and autumn.

"Owing to their sudden advent and their equally sudden cessation, it is most difficult to carry out systematic or pre-arranged experiments."

He therefore confines his remarks to observations made in various parts of the Mediterranean Sea. Speaking of these atmospheric effects, he says (*loc. cit.*)—

"The first case is that due to the effects of lightning discharges, which may or may not be visible at the station where its effects are noticed. As a rule, with the instruments in normal adjustment, the effect of every discharge is to record a signal, the exceptions being very few.

"The method adopted to observe this was to fit an electrical bell, worked by the receiving instruments, close to the observer, and at night observe the flashes and note if the bell rang.

"For detailed observations, it was found more convenient to record the effects on the tape, and this was the method subsequently adopted. On the approach of the area of disturbance towards the ship, the first visible indication generally is —the recording of dots at intervals varying from a few minutes to a few seconds; secondly, the recording of three dots with a space between the first two, thus: (- --), or *e i*, in the Morse Code, and this is the sign most frequently recorded by distant lightning; thirdly, the recording of dashes; the intervals between these then gradually decrease and merge into irregular signs, which have sometimes spelt words in the Morse Code; the effects generally die out more suddenly than they appear.

"They are much more frequent in summer and autumn than in winter and spring—in the neighbourhood of high mountains than in the open sea—in southerly than in northerly winds (in the Mediterranean Sea)—in the front of a cyclonic disturbance of the atmosphere than in the rear, and with a falling barometer than with a rising one. In settled fine weather, if present, they reach their maxima between 8 and 10 p.m., and frequently last during the whole night, with a minimum of disturbance between 9 a.m. and 1 p.m.

"The next cause which is intimately connected with the above is the shorter distance at which signals can usually be received, when any electrical disturbances are present in the atmosphere, compared to the distance at which they can be received when none are present. The distance varies from about 30 to 80 per cent. compared with that obtained in fine clear weather. It does not in any way decrease with the increase of the number of lightning discharges which register their effect on the instruments, at any given time, but rather the reverse, the loss in distance generally preceding the first indications, on the instruments, of the approaching electrical disturbance.

"A very marked case is given as an example: Two ships whose instruments were in perfect order, and whose sea-signalling distance was about 65 miles, opened their distance from each other on a fine, calm, bright day; when they were 22 miles apart the signals died away, though there was no intervening land or other apparent cause for this, but it was noticed that the barometer was falling; the ships closed, and got into communication again. Atmospheric disturbances were then registered on both sets of instruments, and on the ships opening out again, no signals were obtained over 20 miles. The trials were concluded shortly after, owing to intervening land. A few hours later a heavy winter gale came on, and its approach had evidently been foretold by the falling barometer, the loss of distance in signalling, and the electrical disturbances in the atmosphere, as shown by the signals received on the instruments. No lightning flashes were observed.

"On another occasion, during a period of strong but intermittent atmospheric effects, no signals were obtainable between two ships up to the usual maximum signal distance. When separated 50 per cent. beyond this distance, and immediately after a particularly strong and persistent series of electrical discharges, the latter half of a signal, which was being transmitted very slowly, was correctly deciphered at a distance then considered phenomenal, with the instruments employed at the time. A few minutes later the atmospheric effects vanished, and with them all signs of further signals, till the ships had closed to their usual signalling distance. This demonstrates that the actual electrical discharges do not of themselves reduce the signalling distance or transmission of the waves at all times, but that they may, under some circumstances, assist that transmission, possibly by a cumulative effect of the waves emitted by the discharges on the waves emitted by the transmitter, these combining and increasing the effect in the receiver.

"Another observed effect which reduces the usual signalling distance is probably due to the presence of material particles held in suspension by the water spherules in a moist atmosphere.

"The Mediterranean Sea is, for days together, frequently exposed to the force of the scirocco wind; this south-easterly wind is laden with damp, and often charged with salt from spray, and dust particles from the African coast. During the continuance of these winds, the maximum signal distance is generally less than in winds (wet or dry) from any other quarter, the proportional distance being from about 60 to 80 per cent. The effect of a scirocco wind can be and is allowed for in practical wireless telegraphy."

The electric discharges due to atmospheric electricity create electromagnetic waves of an irregular type, which interfere with wireless telegraphy by causing irregular signals. These are technically termed X's. At times they cause the signals to be illegible by interposing irregular dots and dashes in amongst those due to the signals sent. Hence means have been devised for sifting out the waves due to these irregular atmospheric disturbances, and preventing them from influencing the receiving instrument. One of these devices, due to Mr. Marconi, has received the name of an *X-stopper*. The general arrangements of the apparatus will be understood from the accompanying diagrams (see Figs. 29*a*, 29*b*, and 29*c*).[6] According to this invention, the aerial or antenna is not connected directly to the earth through the primary coil of an oscillation transformer, but a condenser and an inductance coil, or a series of condensers and inductance coils, are interconnected. Thus, in Fig. 29*a*, *a* is the antenna, *c* is a condenser, *b* is an inductant coil, *e* is the primary coil of the oscillation transformer, *d* is the secondary coil in connection with the cymoscope, or other detector, and *f* and *g* are earth connections. The connection to earth may be made either as in Fig. 29*a* or Fig. 29*b*. Arranged in a more effective form, the condensers and earth connections are multiplied as in Fig. 29*c*. The operation in the last-described form is as follows: If the antenna *a* is influenced by an irregular disturbance, either a solitary wave or a short train of waves of period not agreeing with that for which the cymoscope is tuned, then these oscillations pass to earth through the earth wire *g*, but they do not set up oscillations in the connected condenser circuit. If, however, a train of waves falls on the antenna of the right wave length, it sets up oscillations in the connected condenser circuits, provided that the circuit consisting of the condenser and that section of the inductance coil lying between the condenser and the point of attachment *p* to the antenna, has such a free time period of

[6] See British Specification of G. Marconi, No. 4869, February 27, 1904.

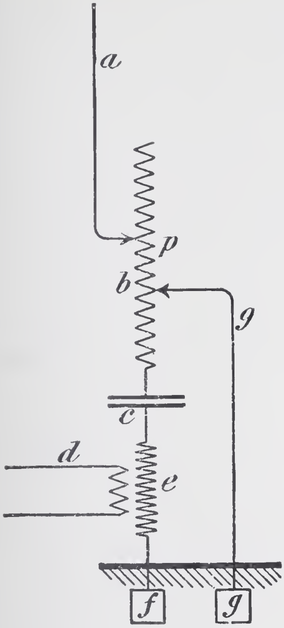


Fig. 29*a*.

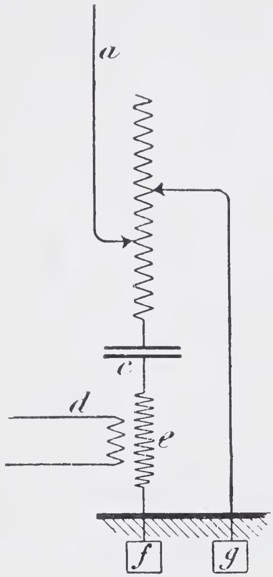


Fig. 29*b*.

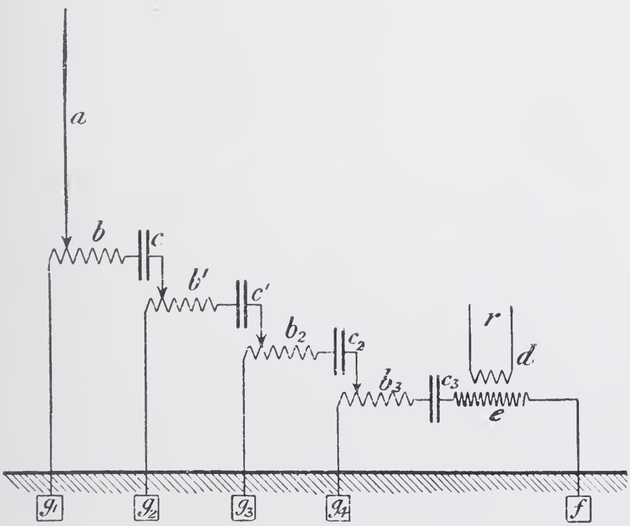


Fig. 29*c*.

Diagram showing the Connections in Marconi's X-stopper. *a*, receiving antenna; *p*, inductance coil with sliding contact, *b*; *c*, condenser; *e*, *d*, jigger in cymoscope; *f*, *g*, earth plates.

oscillation, that it agrees with that for which the cymoscope is tuned. To secure this, the point of attachment *p* of the antenna to the inductance coil *b* must be near a node or point of minimum of potential on the condenser and inductance circuit, whilst, of course, the point of attachment to the earth is also a potential node. Thus, for instance, in reference to Fig. 29*a*, starting from the point of attachment *p* of the antenna to the inductance coil *b*, there are two paths by which the oscillations may travel to earth. One of these paths, *gg*, not having a condenser inserted in it, has no very particular time period of oscillation, the other path, *bcf*, having in it a condenser and inductance, has a definite oscillation time period of its own, and therefore oscillations are established in this latter circuit only if the impulses arriving at the point of attachment of the antenna agree in period with that defined by the inductance and capacity. In the arrangement as shown in Fig. 29*c*, a repeated sifting process is therefore applied to the electrical oscillations.

At each junction of one circuit with the next, oscillations pass to earth, unless they have very nearly the time period defined by the circuit having the condenser in it. Thus, at each step, oscillations of any frequency, different even in a small degree from that for which the cymoscope circuit is adjusted, will be subjected to a process of filtration. The syntonic oscillation will be passed on through the condenser circuit, but the non-syntonic will be passed to earth. Thus, the arrangement figured in Fig. 29*c* constitutes a very effective device, not only for avoiding disturbances due to atmospheric discharges, but also interference due to other non-syntonic or deliberate disturbances.

In reference to this question of the effect of obstacles, we may make mention of some further interesting observations made by Admiral Jackson, R.N., in course of work done in wireless telegraphy for the British Navy. They are concerned with the production of areas of weak reception when ships which are signalling to each other are placed in certain relative positions. Admiral Jackson, in the paper above mentioned (*loc. cit.*), says—

"This phenomenon manifests itself by the gradual weakening and occasionally by the total cessation of signals, as the distance between the two ships increases, up to a certain point, and their reappearance as the distance is still further increased; in the majority of cases the weakening of signals occurs at, or about, half the signalling distance in the open sea, under the same circumstances, which circumstances include the direct connection of the aerial wire to one ball of the nduction coil used for transmission.

"The three following examples are typical cases. Units of distance are given in lieu of nautical miles.

"(*a*) A ship, A, steamed away from a station, B, to ascertain the maximum distance at which she could receive signals in the open sea.

"At 48 units of distance the signals weakened, at 57 they ceased, at 65 they appeared again, and were kept up to 100 units of distance.

"(*b*) Four ships, C, D, E, F, steered as shown in the diagram, the maximum signalling distance between each pair being about 100 units distance.

"(The results of the signals transmitted by D are those specially to be considered.)

"In position (1) D's signals were received by E, F, not by C.
,, ,, (2) ,, ,, ,, ,, ,, F, ,, E, C.
,, ,, (3) ,, ,, ,, ,, ,, C, F, ,, E.

"C did not commence signalling before reaching (2), and her signals were received by D and E, and maintained by them to position (3), when the trial was finished.

"E's signals, which were few in number, were received by C and D in (3), but not by D in (2).

"(*c*) In the third example, ships D and F carried out a similar trial independently. Between 45 and 55 similar units of distance no signals could be exchanged either way, though at 60 units and above, and below 40, the signalling was perfect.

"To further verify that it was the system of transmission that was the cause of this cessation of signals, a syntonic method, of the same approximate frequency of transmission, though of rather less power, was used alternately with the other system. Signals were exchanged perfectly with the syntonic method, but on reverting to the other method the signals again ceased.

"This was tried repeatedly with identical results. Many other similar cases have been recorded, but the effects are not always so equally well marked, even under identical circumstances."

In reference to the cause of this effect, Admiral Jackson says—

"I consider this effect is due to want of synchronism in the oscillatory discharge between the spark balls of the transmitter. This want of synchronism has also been observed by others in the photographs of oscillatory spark discharges. C. Tissot[7] especially remarks that, in his apparatus (presumably used for a wireless telegraph transmitter) the images of the successive sparks are not equidistant, and that the first interval is always greater than the other intervals, which also decrease very slightly. This implies that the first wave emitted is longer than the second, and so on. Owing to the rapid damping of our form of transmitter, probably only the first two or three waves emitted are of any practical value in exciting the coherer in wireless telegraphy at a distance of 30 miles; and to excite it at such distances with the power used in these transmitters, it is probably essential that the effects of the successive waves should be cumulative in their action, and for them to be so they must syntonize with the natural period of oscillation of the receiving circuit, which period, in the cases under notice, was the mean frequency of the waves emitted by the transmitter as nearly as this could be practically adjusted.

"Consider the first two waves emitted, or the interval between the first and fifth sparks of the oscillatory discharge, when the third one is not spaced midway between them; the resulting waves, differing but little in length, and moving with equal velocities and in the same direction, leave a point O (the spark gap), the second starting a mean wave length behind the first one, and in the same phase; at some fixed point, P, in their path, owing to the difference in their length, the two waves will pass that point in the opposite phase, and at a point, Q, approximately double the distance from O that P is from O, they will pass Q, again in the same phase, and so on, as at all points the second wave is a mean wave length behind the first one. *To excite the coherer*, under the conditions presumed to be necessary for long distances, the impulses due to these waves must syntonize with the natural period of oscillation of the receiving circuit, and therefore these successive waves must pass by that circuit (wherever it may be), with the second following in the same phase as the first, or nearly so, otherwise the tendency of the second one will be to weaken or annul the effect of the first one.

"At the point P, therefore, when the waves are in opposite phase, it may be expected that signals will be weak, and at Q, when they are in phase, they *may be* strong, but, owing to Q's distance from O being double that of P, the effect of each individual impulse at Q is only half its effect at P, and Q *may be* the maximum distance from O at which the cumulative effect of the successive waves will excite the coherer, even when they are in phase and in perfect syntony with the receiver circuit.

"I have not yet been able to investigate the exact cause of the non-synchronous emission of the waves, but I attribute these 'zones of weak signals' (as I term them) to this non-synchronous emission of the waves, and to the rapid damping of this form of transmitter, and would observe that when using my syntonic transmitter, in which the damping is less rapid, I have never noticed these effects."

He finally sums up his conclusions in this important paper in

[7] *Comptes Rendus*, March 25, 1901, vol. 132, p. 763; and December 2, 1901, vol. 133, p. 929.

reference to wireless telegraphic communication over sea between ships as follows :—

"(1) That intervening land of any kind reduces the practical signalling distance between two ships or stations, compared with the distance obtainable in the open sea, and that this loss in distance varies with the height, thickness, contour, and nature of the land; and that, based on the results of these observations, it may be concluded that some of the waves of electric induction, transmitted by wireless telegraphy, may pass through, over, and possibly round the land, and are comparable to the passage of ocean waves through or over a reef, or round high land, which waves proceed along their course with diminished energy, after passing such obstructions.

"(2) That material particles, such as dust and salt held in suspension in a moist atmosphere, also reduce the signalling distance, probably dissipating and absorbing the waves.

"(3) That electrical disturbance in the atmosphere also acts most adversely to the regular transmission of these waves, in addition to affecting the receiving instruments by lightning discharges.

"(4) That a system of transmission in which the oscillations are rapidly damped is irregular in its action on distant receivers, owing to the irregularity of the train of waves giving rise to different types of disturbance at different parts of their path, which may not have at certain points the necessary cumulative effect on the receiving circuit.

"(5) That the earth's function in the transmission of waves is most important; but that its importance is secondary to that of the aerial wire, or capacity insulated in the air above the surface of the surrounding sea or earth."

Observations have been made by Major George O. Squier, of the United States Signal Corps, on the absorption of the electromagnetic waves by trees and other vegetable organisms.[8] These originated in the discovery that a very good earth can be obtained for a military telephone line by merely driving an iron nail into the roots of a large tree. It was found that the conductivity of a growing tree in a healthy state for telephone currents is such that the nail need not be driven in quite at the root of a tree, but may be put into the trunk 30 feet or more above the ground with equally good results. This showed that the electrical connection between a tree and the earth is very good, and that the mass of growing widely spread roots of a large tree constitute a "good earth." This led to an attempt to make use of tall trees as wireless telegraph antennæ, by connecting some point near the base of the tree, by means of wire, with some point higher up on the tree trunk, the point near the base of the tree being either close to the trunk or a little way removed from it. It was shown by careful experiments that the tree trunk really did play the part of an antenna, and that the effect was not merely due to the elevated wire. Experiments were then made to ascertain if there was any screening effect from neighbouring trees in the line with the receiving station. The wave length used in most of the tests was about 300 feet in length. No numerical results were given, but it is asserted that marked absorbtive effects due to trees in the mass was noticed.

The author has made many experiments on the obstruction of long electric waves by the buildings of a city. These experiments were made between University College, Gower Street, London, and

[8] Excerpt from Major-General Arthur MacArthur's Report to the War Department, U.S.A., on the Military Manœuvres of the Pacific Division, 1904. See also British Patent Specification, No. 25,610 of 1904, of F. W. Howarth, a communication from George Owen Squier.

his own private house at Hampstead, in the north-west of London. He has found that a wave above 300 feet long does not pass at all well across a city; in fact, it is very difficult to get signals at any distance exceeding a mile or so. On the other hand, a wave having a length of about 1000 feet passes very well through the buildings of a city.

On the occasion of a lecture given by the author at the Royal Institution, in London, messages were transmitted by Marconi apparatus, sending long waves from Chelmsford, Essex, the distance being about 20 miles, and very clear and vigorous signals were received. Such transmission, however, would be impossible with waves of a shorter wave length.

9. The Effect of Sunlight on Long Distance Radiotelegraphy. —In close connection with this part of the subject are Mr. Marconi's interesting observations on the effect of sunlight on the propagation of long electric waves over great distances. In one of his voyages across the Atlantic, when receiving signals from Poldhu on board the ss. *Philadelphia*, he noticed that the signals were received by night when they could not be detected by day.[9] In these experiments, Mr. Marconi instructed his assistants at Poldhu to send signals at a certain rate from 12 to 1 a.m., from 6 to 7 a.m., from 12 to 1 p.m., and 6 to 7 p.m., Greenwich mean time, every day for a week. He states that on board the *Philadelphia* he did not notice any apparent difference between the signals received in the day and those received at night until the vessel had reached a distance of 500 statute miles from Poldhu. At distances of over 700 miles the signals transmitted during the day failed entirely, while those sent at night remained quite strong up to 1551 miles, and were clearly decipherable up to a distance of 2099 miles from Poldhu. Mr. Marconi also noted that at distances of over 700 miles the signals at 6 a.m. in the week between February 23 and March 1 were quite clear and distinct, whereas by 7 a.m. they had become weak almost to total disappearance. This fact led him at first to conclude that the cause of the weakening was due to the action of the daylight upon the transmitting aerial, and that, as the sun rose over Poldhu, so the wave energy radiated, diminished, and he suggests as an explanation the known fact of the dissipating action of light upon a negative charge.

Although the facts seem to support this view, another explanation may be suggested. It has been shown mathematically by Professor Sir J. J. Thomson that gaseous ions or electrons are set in motion in the direction of propagation by a long electric wave travelling through them, and they therefore can absorb the energy of a long electric wave when passing through a space through which such electrons are scattered.[10]

It is well known that ultraviolet light has the power of ionizing gaseous molecules or separating from them electrons. Hence, since the sun's ultraviolet light is largely absorbed in the upper atmosphere, it may well be that the portion of the earth's atmosphere which is

[9] See *Proc. Roy. Soc.*, June 12, 1902, "A Note on the Effect of Daylight upon the Propagation of Electromagnetic Impulses over Long Distances," by G. Marconi.

[10] See *Phil. Mag.*, August, 1902, ser. 6, vol. 4, p. 253, J. J. Thomson, "On Some Consequences of the Emission of Negatively Electrified Corpuscles by Hot Bodies."

facing the sun will have present in it more electrons or gaseous ions than that portion which is turned towards the dark space, and it may therefore be less transparent to long Hertzian waves.[11] In other words, clear, sunlit air, though extremely transparent to light waves, may act as if it were a slightly turbid medium for long Hertzian waves. The dividing line between that portion of the earth's atmosphere which is impregnated with gaseous ions or electrons is not sharply delimited from the part not so illuminated, and there may be, therefore, a considerable penetration of these ions into the regions which may be called the twilight areas. Accordingly, as the earth rotates, a district in which Hertzian waves are being propagated is brought, towards the time of sunrise, into a position in which the atmosphere begins to be ionized, although far from as freely as in the case during the hours of bright sunshine.

Mr. Marconi states that he has found a similar effect between inland stations, signals having been received by him during the night, between Poldhu and Poole, with an aerial the height of which was not sufficient to receive them by day. It has been found, however, that the effect simply amounts to this, that rather more power is required by day than by night to send signals of Hertzian waves over long distances.

Neither the effect of earth curvature nor those due to atmospheric ionization by sunlight are detectable over short distances, such as 100 miles or less. It is only when the telegraphic distance amounts to some hundreds of miles that they begin to make themselves evident. Recent advances have, however, tended to minimize their importance. They are greatly influenced by the length and nature of the wave radiated, and are perfectly capable of being brought under control.

Professor Sir J. J. Thomson has shown (*loc. cit.*) that if electric waves of length λ, and having a maximum magnetic force, H, are travelling in a medium containing free electrons, each electron having a negative charge, e, and mass, m, then the electron is moved forward in the direction of propagation. The maximum velocity w imparted to each electron in the direction in which the wave is moving is given by the expression—

$$V^2 - (V - w)^2 = \frac{\lambda^2 H^2 e^2}{4\pi^2 m^2}$$

where $V = 3 \times 10^{10}$. If e is reckoned in electromagnetic units, the ratio of charge to mass for an electron $= \frac{e}{m} = 10^7$, and $\pi^2 = 10$ nearly. Hence, if w is small compared with V, we have—

$$w = \frac{1}{2} \cdot \frac{\lambda^2 H^2 10^{14}}{4\pi^2 . 3 \times 10^{10}} = \frac{\lambda^2 H^2}{24} 1000$$

The magnetic force H of any wave is always a numerically small quantity in the electromagnetic system of units, and hence the velocity w is small unless λ is very large.

[11] The opinion that ionization of the air by sunlight is a cause of obstruction to Hertzian waves propagated over long distances has also been expressed by Mr. J. E. Taylor. See *Proc. Roy. Soc.*, 1903, vol. 71, p. 225, "Characteristics of Earth-current Disturbances and their Origin."

Accordingly, the presence of numerous free electrons in a space through which long electric waves are passing will rob these waves of energy. The energy imparted to the electron to give it a maximum velocity, w, is $\frac{1}{2}mw^2$, and from the above expression this is seen to be equal to $\frac{\lambda^4 H^4 e^4}{128\pi^4 m^3 V^2}$.

If there are N electrons per cubic centimetre, then, since the wave energy per unit volume for a medium of unit permeability is $\frac{1}{2}H^2$, we see that the energy taken from the wave per cubic centimetre of space is—

$$\frac{N\lambda^4 e^4 H^2}{64\pi^4 m^3 V} \cdot \frac{H^2}{2} = \frac{1}{a} \cdot \frac{H^2}{2}$$

By means of an apparatus devised by Ebert and by Gerdien it is possible to determine the conductivity of the air, and hence the number of ions N per cubic centimetre. With this apparatus Boltzmann found during a voyage across the Atlantic 1150 positive and 800 negative ions per cubic centimetre. Also over the same ocean, A. S. Eve found from 600 to 1400 positive and 500 to 1000 negative, the ratio of positive to negative varying from 1·04 to 1·83. These numbers do not differ greatly from those found over large land areas, such as Germany or Canada. The above expression shows that the wave weakening is reduced by using a wave of small amplitude or small magnetic force H, and for that reason it is greatest in the neighbourhood of the sending antenna.

Professor J. Zenneck has, however, discussed the question whether such atmospheric conductivity as is shown to exist can bestow an opacity upon it for the long electromagnetic waves employed in radiotelegraphy. The conclusion to which he was led is that the effect of daylight must be sought for rather in an action of light upon the sending antenna than upon the air itself.[12] There is, however, a very distinct difference in the ease with which wave lengths of different lengths are propagated across the Atlantic.

There appears to be at almost all times something in the terrestrial atmosphere which acts towards long electric waves as mist or fog acts towards light. Also just as there are occasionally for vision exceptionally clear atmospheric conditions in which distant objects stand out sharply on the horizon, so there are times when radiotelegraphic waves seem to be propagated with very little loss, and ships or stations whose normal range of communication is 200 miles or so send or receive 1000 miles or more. If this want of transparency to long electric waves is due to electrons in the atmosphere we may perhaps speak of the cause of the obstruction as an electronic fog. On these matters Mr. Marconi made some interesting remarks in his Nobel Prize Lecture, delivered December 11, 1909. He says :—

"It has been observed that an ordinary ship station, using about half a kilowatt, the normal range of which is not greater than 200 miles, will occasionally transmit messages across a distance of over 1200 miles. It often occurs that a ship fails to communicate with a

[12] See J. Zenneck, "The Propagation of Plane Electromagnetic Waves over a Plane Conducting Surface with Reference to Wireless Telegraphy," *Annalen der Physik*, vol. xxiii., 1907.

near-by station, but can correspond with perfect ease with a distant one." Also he remarks, "Although high-power stations are now used for communicating across the Atlantic, and messages can be sent by day as well as by night, there still exist short periods of daily occurrence during which transmission from England to America, or *vice versâ*, is difficult. Thus, in the morning and evening, when, in consequence of the difference of longitude, daylight or darkness extends only a part of the way across the ocean, the received signals are weak and sometimes cease altogether. It would almost appear as if electric waves in passing from dark space to illuminated space and *vice versâ* were reflected in such a manner as to be diverted from their normal path."

"Another curious result on which hundreds of observations continued for years leave no further doubt, is that regularly for periods at sunrise and sunset, and occasionally at other times, a shorter wave can be detected across the Atlantic in preference to the longer wave normally employed. Thus at Clifden and Glace Bay, when sending on an ordinary coupled circuit arranged so as to simultaneously radiate two waves, one 12,500 feet and the other 14,700 feet, although the longer wave is the one usually received at the other side of the ocean, regularly about three hours after sunset at Clifden and three hours before sunrise at Glace Bay, the shorter wave is alone received with remarkable strength so regularly that the operators tune their receivers to the shorter wave at the times mentioned as a matter of ordinary routine."

According to R. A. Fessenden (see his British Patent Specification, No. 20,466 of 1908) this atmospheric absorption for long electric waves reaches a maximum for waves of 5000 to 10,000 feet in wave length, but decreases for longer wave lengths, so that electromagnetic waves, having a wave length of 20,000 feet, travel as well by day as by night.

These curious facts show that we have still much to learn concerning the best conditions for the propagation of long electric radiotelegraphic waves over large distances by day and by night. It is also probable that there may be seasonal and secular variations offering better conditions at one time of the year or one portion of a century, as well as occasionally favourable times for long-distance radiotelegraphy.

10. The Effect of Earth Curvature on Long Distance Radiotelegraphy.—When radiotelegraphy over very long distances, such as the Atlantic Ocean, was first accomplished, surprise was expressed that the electromagnetic waves could travel so far round the earth as 45° of longitude whilst still retaining intensity enough to be detected. It is, however, a familiar fact that waves of light and also sound or air waves bend round an obstacle to a greater or less extent. In the case of light this phenomenon is called diffraction. The explanation of it is as follows:—

Let C (Fig. 30) be a radiant point emitting circular waves. At any instant let the wave have arrived at the position P. Let O be any point further on. Then by Huyghen's principle the effect or disturbance at O is due to the sum of all the secondary waves propagated outwards from all points in the circular wave front which has reached P. With O as centre describe a number of arcs of circles, the radius of each being greater than the next one by $\frac{1}{2}\lambda$, where λ is the wave length, and let these arcs cut the wave front into

sections or elements PM, MM_1, M_1M_2, etc., which we shall call half wave-length elements. It is clear that the length of the arc PM is greater than the length of the arc MM_1 and so on, and that as we move outwards along the wave front these arcs tend to become equal. Corresponding to every point in the arc MM_1 there is therefore a point in the arc PM such that the difference of their distances from O is equal to $\frac{1}{2}\lambda$. Hence the waves sent out by these two points will be in opposition as regards phase. We may assume that the number of wave-making points or centres of disturbance in each little arc is proportional to the length of the arc. It is therefore evident that the further the arcs are taken from the pole P of the wave, the more completely they neutralize each other's effects at O when taken pair and pair consecutively. Accordingly, the disturbance at O will be chiefly due to the middle portion of the wave, viz. that which lies near P, and will be destroyed by any opaque object placed near the central portion of the wave.

In the case of light waves the wave length is very small compared

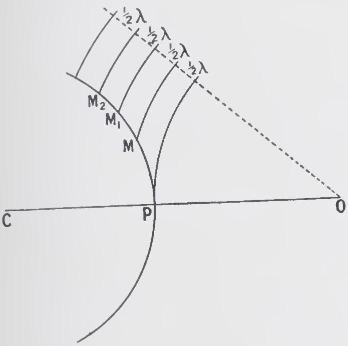


FIG. 30.

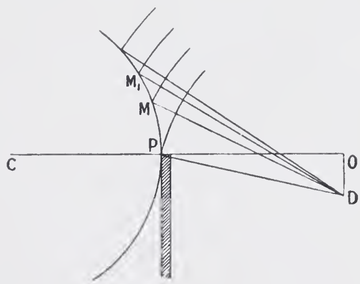


FIG. 31.

with the distances OP, CP, and hence the effective portion of the wave front is very closely confined to a small area round the pole P. If, therefore, an opaque screen is placed so as to cut off half the wave, only a very small part of the space within the geometrical shadow will receive light, viz. up to such a limiting distance OD, bounded by a point D, from which, if radii increasing by $\frac{1}{2}\lambda$ are drawn, the lengths of the arcs PM_1 MM_1 cut off on the wave front differ by a sensible amount. The depth OD (see Fig. 31) will increase with the wave length, because the greater the wave length the further round the wave front does the inequality in length of the half wave length elements extend. Accordingly, in the case of light waves there is an illumination which extends slightly within the boundary of the geometrical shadow, but fading off, and in any case very small. On the other hand, if we are dealing with long electric waves, or with sound waves of which the wave length is not small compared with the distances PO or PC, then this bending round or diffraction is very sensible, and there is no sharply defined edge to the shadow.

In the case of radiotelegraphic electric waves having a length of 1000 feet or more, natural objects, such as cliffs or hills, do cast what

may be called electromagnetic shadows; but the longer the wave length which we employ, the less well marked is the effect.

The wave lengths employed in transatlantic wireless telegraphy are of the order of 10,000 or 12,000 feet, or, say, 2 miles in wave length. Hence, compared with these waves, the size of the earth itself is as the size of a small shot 2 millimetres in diameter to rays of yellow light.

Experience proves that a very considerable bending of these long electric waves round the earth's surface can take place, but the question arises whether this bending takes place in virtue of actions which are entirely the same as luminous wave or air wave diffraction. Some calculations were made by Professor H. M. Macdonald in 1903,[13] but the results of these were not entirely approved by other physicists.[14]

In a subsequent paper on "The Diffraction of Electric Waves round a Perfectly Reflecting Obstacle" (see *Phil. Trans. Roy. Soc.*, Vol. 210, p. 113..1910), Prof. Macdonald has extended his investigations and given a table showing the decay in amplitude for waves 1000 feet long propagated round the earth.

The matter has also been considered by Professor Poincaré, in a series of articles on the theory of Hertzian wave telegraphy.[15] His view appears to be that the passage of a long electromagnetic wave round the earth to such an extent as 45° of longitude is an effect of diffraction. Lord Rayleigh has, however, expressed the opinion that there is something not yet entirely explained by diffraction in the phenomenon. The difficulty, however, is to put any theory to the test by measurement. We know that waves sent out from an antenna in England, having a length of, say, 10,000 feet, or even much less, are detectable across the Atlantic, and therefore have travelled round an arc of 45° along the earth's surface. We are not able, however, to say how the intensity of these waves on arriving differs from the intensity they would have had if, under otherwise similar conditions, they had travelled over the same distance along a plane instead of round a sphere, since the pure diffraction effect is overlaid by an absorbtive effect due to the ionized atmosphere. Also there is a wave-weakening due to absorption by the earth's surface as explained in § 14, chap. viii., both of which operate to obscure the pure curvature effect.

In the lectures mentioned M. Poincaré has given a differential equation, derived from Maxwell's equations, expressing the vector potential at any point on a sphere due to a wave disturbance created at any other, but he has not left the matter in such a form that it can be submitted to calculation.

The whole question has more recently been re-discussed by Dr. J. W. Nicholson in a series of papers in the *Philosophical Magazine* for February, March, April, May, 1910 (see *Phil. Mag.*, Vol. 19, pp. 276, 435, 516, 757..1910, "On the bending of Electric Waves round the Earth"). It has also been re-considered by M. H. Poincaré (see *Comptes Rendus*, April 29, 1909, and *Rendiconti dei Circolo Matematico*

[13] See H. M. Macdonald, *Proc. Roy. Soc. Lond.*, vol. 71, A., p. 251, 1903; also Vol. 72, p. 59, 1904.

[14] See Lord Rayleigh and M. Poincaré, *Proc. Roy. Soc. Lond.*, vol. 72, A., 1903.

[15] See *La Lumière Électrique*, vol. iv., 2nd ser., November 28, December 5, 12, 19, 1908, "Conférences sur la Telégraphie sans fil." See especially December 12, p. 323, 1908.

di Palermo Marzo-Aprile, 1910, and *Jahrbuch der Drahtlosen Telegraphie und Telephonie*, Vol. 3, p. 445 .. 1910).

The papers by Dr. Nicholson are very long and difficult to abstract, but one conclusion of his is undoubtedly important. His analysis of the operations taking place when an electric oscillator is placed on the surface of a conducting sphere, the ratio of diameter of sphere to wave length being large, say 5000 to 50,000, shows that the effect is to produce a series of true diffraction bands contained between two cones with apex on the oscillator, their angles differing by a small amount. It appears, moreover, that the actual amount of bending of long electric waves round the earth for a range of 45° of longitude is greater than can be accounted for by true diffraction. This being the result of analysis, Nicholson considers that other causes, such as reflection from a layer of ionized air at high altitudes, must be sought for as an aid to diffraction in explaining this abnormal bending. It may be that there is something of the nature of a reversed mirage effect, in virtue of which the waves are deflected round the earth by the reflective action of highly ionized layers of air in the upper atmosphere.

The matter is complicated not only by the effects of atmospheric ionization, but also by the conduction effects in the earth. In addition to the Hertzian wave propagated through the æther outside the terrestrial sphere, there is probably a conducted wave travelling in or on the soil or water. The earthed sending antenna, the earth and the earthed receiving antenna constitute one conducting mass, in which at one place a high frequency alternating E.M.F. is impressed. The result is not only the detachment of a Hertzian wave by which energy leaves the oscillator, but changes of potential are propagated through the earth and make themselves felt at the receiver.

The fact, however, remains that long-distance radiotelegraphy is not inhibited by earth curvature within certain limits, although the anticipations which have been indulged that it may be possible to communicate from England to New Zealand by radiotelegraphy have not at the present time exact scientific foundation.

11. Military and Portable Stations.—The great advantage of being able to communicate considerable distances over land without continuous wires by means of radiotelegraphy has rendered it an indispensable means of communication in connection with military operations. For this purpose it is necessary to have portable stations which can be transported easily from place to place, the parts of which must therefore be capable of being loaded upon the backs of mules, or else contained in light carts, which can be drawn over rough ground; everything being so fitted as to present the least possible opportunity for getting out of order with rough usage. The first element in these portable stations is the portable antenna. This generally consists of a light mast 60 to 70 feet in height, made in sections which can be jointed together like a fishing rod, and easily capable of being erected and taken down, and transported on the backs of pack-mules.

The following is a description of the probable apparatus devised and supplied by the Marconi Wireless Telegraph Company in connection with their Military Wireless Telegraphic outfit. For the

illustrations in Figs. 32–37 inclusive the author is indebted to the kindness of the Marconi Company. The Company supply three sets of apparatus designed for communicating respectively over distances of 25 kilometres (15 miles), 35 kilometres (21 miles), and 100 kilometres (60 miles). The apparatus has been designed specially with a view to making it as light, compact, and efficient as possible, and capable of sustaining the severe treatment to which it is liable under working conditions in the field. The stations are all provided with directive antennæ consisting of one or two wires stretched partly in a vertical and to a much greater extent in a horizontal direction, these wires being supported by portable masts. The directive antennæ, therefore, not only give the power of locating another communicating station, but also to a considerable extent prevent the radiation from being sent out in undesired directions. The smallest of the sets (No. 1) is designed for use with cavalry, and is so arranged that the apparatus can be carried on the backs of two horses or mules (see Figs. 32, 33). It comprises two portable masts, one 15 feet high in three sections, and the other 25 feet high in five sections. These are put together like fishing rods, and erected in a few minutes. These masts support two approximately horizontal wires each 400 feet long kept 5 feet apart at the ends by a light sprit. The transmitting set comprises a small dynamo fixed to a sort of bicycle frame (see Fig. 34) and driven by a man who sits on a bicycle seat and works pedals. This small dynamo has an output of about 150 watts, and it supplies current to an induction coil and transmitting set comprising a condenser, oscillation transformer, spark gap, and transmitting key, which are fixed upon a table which can be erected in a tent. The receiver consists of a small Marconi magnetic detector and a pair of telephones. The earthplate consists of a strip of copper about 3 feet wide and 25 feet long which is wound up for transit on a drum. The aerial wires are also wound up on small drums, and also the supporting stays for the masts. The total weight of this set of apparatus including tent and packing-cases is 380 lbs., and is packed for transit on two Morgan pack-saddles which weigh 45 lbs. each, so that the total burden on each horse or mule is 240 lbs.

The No. 2 size station is very similar to the above and has a longer range. The transmitting apparatus is more powerful than in the cavalry stations, the dynamo being driven by four or six men. The masts are 30 feet high and divided into five sections, which are carried for transit on brackets fixed to the side of the cart. In the cart is an apartment set aside for the dynamo and other supplies and spares; the dynamo, in this case, having an output of 300 watts. In both these sets provision is made for rapidly locating the direction of other wireless stations within range. To do this, only one antenna wire is used; the far end, instead of being supported by a fixed mast is attached temporarily to the top of a pole which is carried in a vertical position by one man and another man keeping the wire taut by means of a rope guy attached to the top of the pole. These two men then walk in a circular direction round the other mast, which is fixed and supports the end of the earth wire, which is attached to the receiver. The operator listening at the receiver then endeavours

FIG. 32.—Marconi Military Wireless Telegraph Apparatus packed for transit.

FIG. 33.—Marconi Military Wireless Telegraph Apparatus packed for transit.

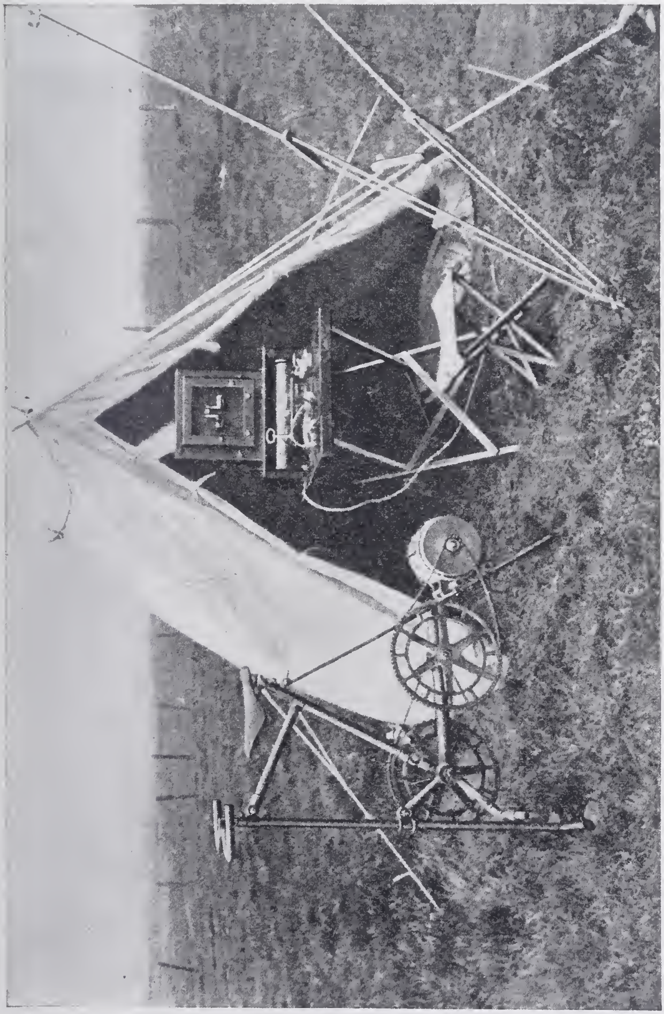


Fig. 34.—Marconi Military Wireless Telegraph Transmitting and Receiving Apparatus set up for use in the Field.

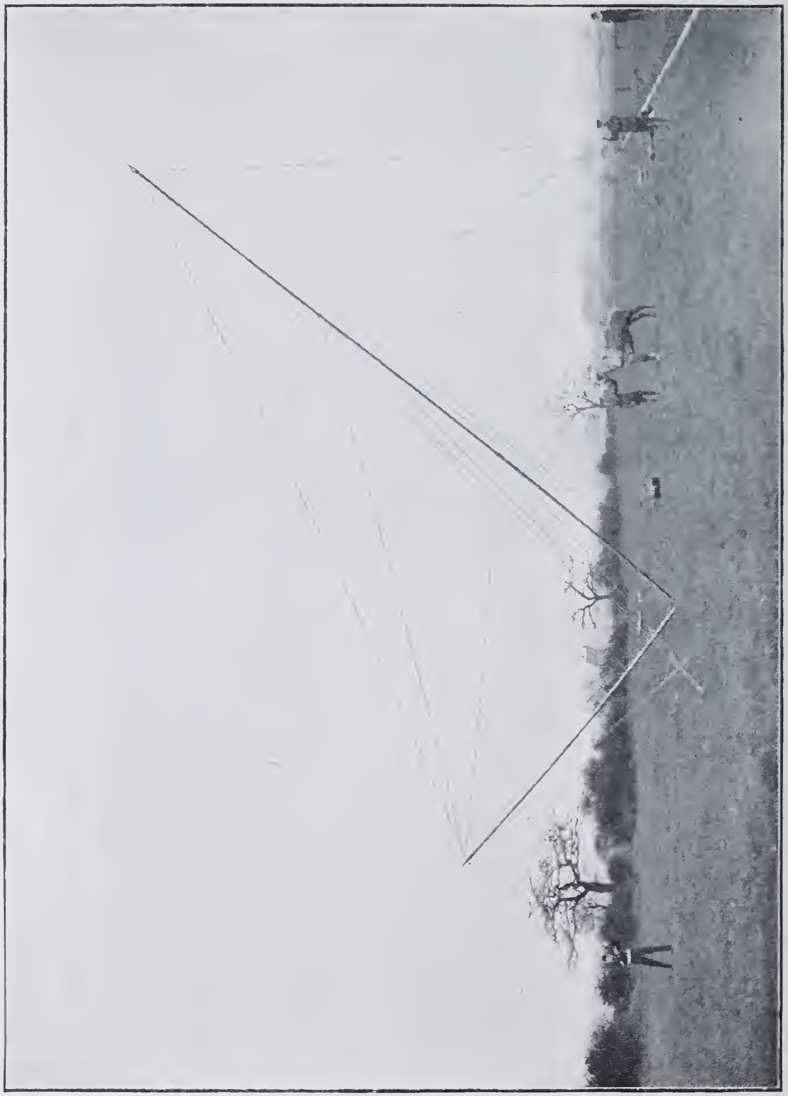


FIG. 35.—Erecting a Marconi Wireless Telegraph Military Mast in the Field.

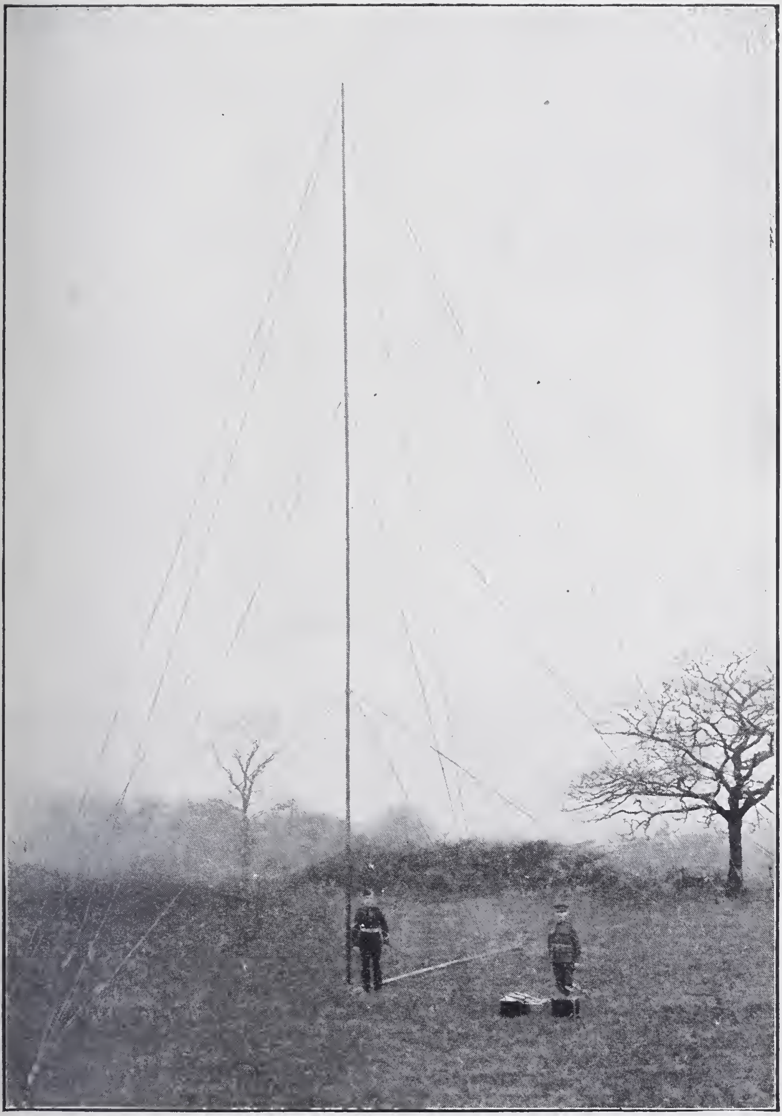


Fig. 36.—Military Mast for Marconi Wireless Telegraph erected in the Field.

Fig. 37.—Marconi Directive Antenna and Radiotelegraphic Station for Military Wireless Telegraphy.

to ascertain in what direction to the horizontal portion of the antenna the signals are loudest, and when this is found, he knows that the sending station is located in a direction exactly opposite to that towards which the free end of the antenna is pointing.

Set No. 3 has a working range of 60 miles or more, and differs in the use of a more powerful transmitter, the energy being supplied by a 1-kw. self-exciting alternator driven by a water-cooled petrol engine of 2 h.p. The antenna consists of four horizontal wires, each 450 feet long, supported on five masts 50 feet high. The masts, complete with stays, beds, and fittings, weigh only 125 lbs. each, and can be erected in a very short time by two men using a special hoisting derrick. The complete set, including spare parts, weighs about 12 cwt., and is contained in a small four-wheeled cart. For the greatest possible speed in erection, six men and one non-commissioned officer are required for each of the two smaller stations, and fifteen men and two officers for the large set. With a little experience on the part of the men erecting the mast, the small set can be got ready for working in about five minutes, and the large one in about half an hour. The masts are erected in the following manner:—

The different sections of the mast are laid on the ground and put together, generally in three parts, each of which may consist of one or more sections. Imagine the mast lying on the ground in a direction north and south. Guy lines of equal length are then laid out on either side of the mast and pinned down to pegs placed in the ground on either side of the mast at equal distances from its foot, on a line running east and west through the foot of the mast. The foot of the mast is attached to a rotating socket, to which also is attached another shorter lever called a derrick, and from this derrick guys proceed upwards to the ends of the sections of the mast of such length that when the derrick and the mast are at right angles, these guys are tight. It will then be seen that if the outer end of the derrick is pulled downwards the mast will be raised gradually into a vertical position, and will be prevented from falling over sideways by the lateral guys which keep tight in all positions of the mast (see Fig. 35). As the mast goes up it has to be prevented from falling over towards the derrick by men who hold on at the guys which extend in a direction from the mast opposite to the guys attached to the derrick, and when the mast is elevated into a vertical position, the derrick is lying on the ground (see Fig. 36), and the mast is supported by four sets of guys. The process of elevating the mast and its final position will be easily understood from Figs. 35 and 36. A larger set supplied by the company is called the $1\frac{1}{2}$-kw. set, and is intended for working over a distance of 100 miles for military operations on a large scale. It comprises a $1\frac{1}{2}$-kw. alternator driven by a 4-h.p. internal combustion engine. The whole outfit is contained in two 2-wheeled carts, of which one carries the generating and the other the operating plant. The aerial is of the Marconi directive type, and consists of a double length of 49/28 phosphor-bronze cable 260 feet long, separated by three separators 12 feet long, and supported on three 60 feet masts, so that 400 feet of the antenna are horizontal and 60 feet vertical (see Fig. 37).

The wire is insulated from the sprits and masts by means of ebonite insulators. The earth plate consists of four sheets of copper, which are laid on the ground, and act partly by making direct earth connection and partly as a balancing capacity. Care should be taken to select a spot, if possible, for erection where the earth is damp. The current is supplied to the sending apparatus from a $1\frac{1}{2}$-kw. rotary converter—that is, a continuous-current dynamo with slip rings on its shaft connected to two points 180° apart on the continuous-current winding of the armature. This machine is capable of being used in various ways. If it is coupled direct to the engine it can generate, not only alternating current taken off the two slip rings, but a continuous current can be drawn from the commutator for charging accumulators or other purposes. If disconnected from the engine it can be driven from a continuous-current supply and alternating current drawn off the slip rings. It is supplied with a rheostat for regulating the magnetic field, and with a double-pole main switch. This converter is driven by a direct coupled 4-h.p. petrol engine with the usual accessories. The sending apparatus comprises a low-frequency transformer receiving alternating current at a frequency of about 100 from the converter slip rings, and supplying high-tension alternating current to the condenser in the oscillatory circuit. The oscillatory circuit is either directly or inductively coupled to the antenna, and the oscillatory circuit contains also a spark gap. The low-frequency transformer is wound with two coils on the primary and secondary, which can be joined in parallel or in series, as required. The condenser is built up with plates of ebonite sandwiched in between metal plates contained in a box which is full of oil, and the condenser is divided into two sections which can be joined in series or parallel. In addition, there is a low-frequency choking coil between the alternator and the low-frequency transformer, and a pair of air or high-frequency choking coils between the condenser and the high-tension side of the low-frequency transformer. One point on the oscillatory circuit is connected to the antenna and the other, through a short spark gap, to the earth. The signalling key is inserted in the low-tension side of the low-frequency transformer. It consists of a relay key and an electromagnetic operating key, which closes the primary circuit of the transformer when the operating key is depressed. When the relay key is raised, the magnet of the operating key keeps the circuit closed until the current passes through a zero point, when the contact opens without spark. As already mentioned, the connection between the lower end of the antenna and the earth is made through a small spark gap. This offers no obstruction to the passage of the sending oscillations; it is, however, a perfect insulation for the feeble current of reception, and by taking a lead from the upper spark ball through the receiving apparatus to earth the latter can remain permanently connected, thus avoiding the inconvenience of any device for switching over the antenna from receiver to transmitter alternately. All that is necessary is to short circuit the telephones when sending, to spare the operator the distressing noise. The receiving apparatus comprises a multiple Marconi tuner as already described, and a Marconi magnetic detector with a pair of head telephones.

The magnetic detector is an instrument particularly suitable for military field work on account of its simplicity and the absence of any difficult adjustments. The standard instrument has two sets of winding and magnets, one on either side of the band of iron wires; these are not used together, but in case of any accident to one the other can replace it. The antenna for this set is a directional antenna 400 feet horizontal and 60 feet vertical, upheld on three masts, which are made in six sections of 10 feet each (see Fig. 37). For the erection of the masts and aerial a piece of ground is required comparatively level, free from dry sand and rock, and not less than 50 feet wide and 500 feet long in the direction of the communicating station. The three masts are arranged in a straight line, passing centrally down the length of the strip of land and placed 200 feet apart, the antenna being brought down vertically at one end and attached to the operating part. Detailed instructions are furnished by the Company for the erection of the masts.

With regard to the generating and transmitting plant, it may be mentioned that the engine and dynamo are mounted on the same bedplate and fixed in the cart, which also contains the following apparatus: a small switchboard, the low-tension adjustable choking coil in a wooden case, the sending key, the low-tension transformer, two high-tension choking coils, the oscillation transformer or jigger and condenser, as well as the magnetic detector and the multiple tuner. The transformer and condenser in the transmitter box are oil insulated, but this oil is emptied out after use and refilled again from a drum in which it is carried whilst moving.

Similar portable sets by various makers are now in common use in connection with the Intelligence and Signalling Departments of the various European foreign armies, and have become indispensable in connection with modern methods of strategy, in which the opposing forces are scattered over wide areas during a campaign.

In Fig. 38 is represented the general arrangements of a portable station employing the Von Lepel discharger, as described in Chap. VIII. § 16.

12. The Efficiency of Radiotelegraphic Stations.—There are several points of view from which we may regard the performance of radiotelegraphic stations. We may in the first place consider merely the success of their operations regardless of questions of cost. The fact of being able to communicate between two places without any interconnecting wire is in itself an interesting and important feat, but when once it is done, we next ask whether the process can be continued with such regularity as to enable it to take its place amongst commercial means of communication. We may call this the attainment of efficiency of performance. Later on we may proceed to ask how far the process can be conducted in competition with other methods as regards cost, and this leads to the consideration of the energy expenditure, depreciation of plant, and cost of labour involved. The great obstacles which have interfered with efficiency of performance are the difficulties connected with the isolation of stations and atmospheric electrical disturbances; in other words, making the receiver immune from disturbance by electric waves due to natural electric discharges, or the operation of stations other than the one

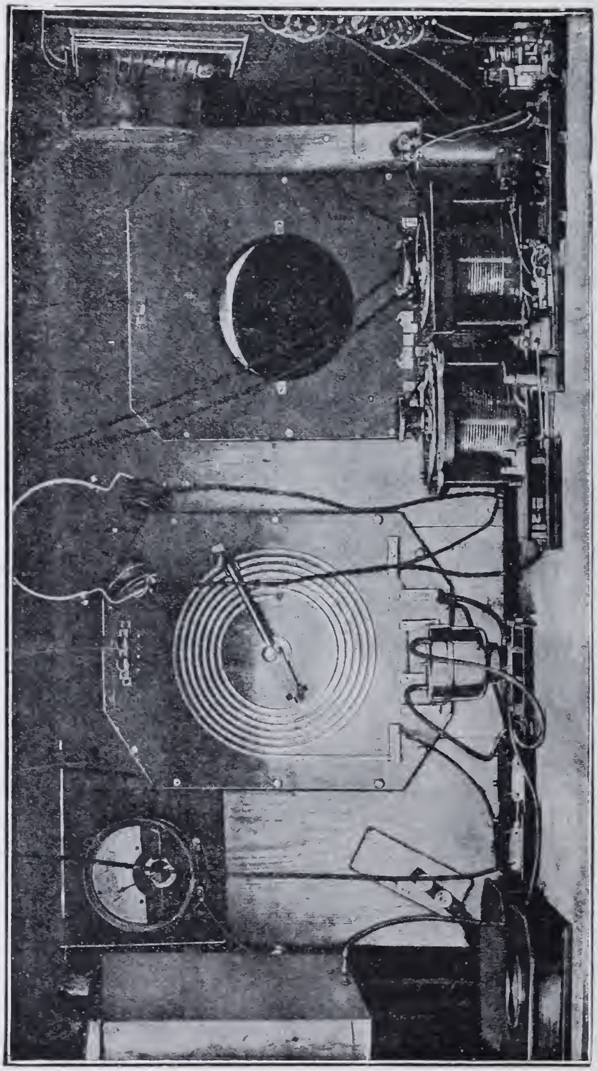


Fig. 38.—Transmitting and Receiving Apparatus in a Portable Station employing the Von Lepel Discharger.

from which it is desired to receive signals. We have considered already the means so far adopted for the solution of this problem. Whilst it cannot be said that the difficulties are completely overcome, yet they are so far under control that radiotelegraphy has taken its place as an indispensable means of communication, especially over sea and between ships. Aided also by the rules of the Convention and by national legislation, unnecessary disturbance of the æther is as far as possible prevented, and we may say that whilst the efficiency of performance of radiotelegraphic stations is not yet ideal in its perfection, it is well within those limits necessary for practically useful and for commercial work.

Accordingly, questions of cost or energy efficiency are now in turn being considered. At the outset one of the objections raised against radiotelegraphy, especially long distance, was the expenditure of energy needed for its operations as compared with that involved in telegraphy with wires. This, however, is merely part of a larger question. The cost of any undertaking in which scientific plant is utilized for commercial purposes may be properly divided into three parts: (1) The interest on the capital outlay necessary to establish the plant and appliances; (2) the cost of working it and conducting its operations; and (3) the allowance for depreciation or antiquation of plant, and for renewals and repairs. From a commercial or business point of view, it is the total cost under all three of the above headings which matters, and not merely one of them taken alone.

In the case of submarine cables the most important items are the capital outlay and the cost of repairs and renewals. The capital outlay on a deep-sea submarine cable averages about £200 per mile or more in initial cost, and repairs are frequently very expensive. A single repair has been known to cost even £70,000. On the other hand, the energy expenditure and actual cost of working is small. Nevertheless, the whole cost of submarine cable-working and the charges which must be made for messages if the undertaking is to be commercial depend upon all the costs taken together.

On the other hand, in the case of radiotelegraphy, the capital outlay on plant or apparatus is relatively to the cost of cables very small. Also the cost of repairs is not large, assuming the absence of exceptional events, such as fires or earthquakes, which may destroy a large station entirely. Hence the fact that there is a larger expenditure of energy in sending any given message radiotelegraphically compared with that by cable is only a limited aspect of the case, and does not imply that the total cost is any more. There is abundant evidence to show that on the whole it is much less. Nevertheless, the question of the sources of energy loss in case of radiotelegraphic apparatus is very important. Sufficient data have been gathered to show that the actual expenditure of energy in true æther wave-making is comparatively small, and that in radiotelegraphic transmitters, as at present constructed, the internal energy dissipation is very considerable. There is, therefore, great room for improvement in this respect. It is important, therefore, to ascertain the sources of this loss, and to improve the energy efficiency of transmitters. Taking the case of the ordinary spark-transmitter, we have first the internal losses in the

alternator, or rotary transformer. Since the power factor of the transmitter plant is small, these internal losses in the alternator may be considerable unless the machine is designed specially for working on a low-power factor circuit.

In the next place energy losses are incurred in the step-up transformers, but these can be minimized by careful design. In the oscillatory circuit we have these energy losses in the condensers, and resistance losses in the inductance and in the spark. The condenser losses are by no means insignificant if glass condensers are used, and hence air condensers are preferable when space permits.

A serious source of loss is generally the bad design of the inductance and connecting circuits. These may be kept down, however, by a proper stranding of the conductors—making them of plaited silk-covered No. 40 H.C. copper wire, and avoiding the use of thick copper strip or coarsely stranded cables.

The energy losses in the spark are unavoidable, but are, no doubt, much diminished by the employment of quenched sparks instead of long single persistent sparks.

The power given to the step-up or charging transformer can be measured by a Wattmeter in the usual way, and the internal losses in this transformer, viz. the iron core and copper or resistance losses, also determined for various values of the current supplied. Hence we can find by difference the power supplied to the oscillatory circuit.

By the measurement of the decrement of this circuit we can ascertain, as shown in § 9, Chap. VIII., the resistance losses, including those in the condenser and spark. Hence by difference again we can ascertain the power given to the antenna, and if the high frequency resistance of the antenna is ascertained we can finally ascertain the power expended in radiation after deducting the resistance losses due to the earth connection, if any.

The reader may be referred for some efficiency measurements of the above kind or on small spark transmitter apparatus to a paper read by the Author before the Institution of Electrical Engineers of London in November, 1909, "On some quantitative measurements in connection with radiotelegraphy," and to one read at the same date by Dr. Eccles and Mr. Makower, "On the efficiency of short-spark methods of generating electrical oscillations."[16] In the first paper it is shown that for the spark transmitter used the power expended in making electric waves was rather less than 10 per cent. of that given to the charging transformer, and in the latter paper it is shown that in the case of a discharger of the Von Lepel type the fraction of the power given to the discharger which appeared as oscillations in the antenna did not much exceed 14 per cent.

It is highly probable, therefore, that at the present time for most spark transmitters less than 10 per cent. of the applied power is represented by the radiated waves, and the efficiency of the transmitter associated spark producer and antenna, considered as an appliance for transforming electric current energy into electric wave energy, is not on the whole greater than that of an electric arc lamp as an energy transforming device of a similar kind. There is, therefore,

[16] See *Journal of the Institution of Electrical Engineers*, vol. 44, 1910, pp. 344 and 387.

abundant room for improvement in this respect, and it is only by the application of careful and correct methods of measurements that we can ascertain where the sources of loss exist and the extent of the remedy possible.

Whilst this chapter is passing through the press a paper has, however, been published by Count Von Arco in the *Elektrotechnische Zeitschrift*, Heft 20, 1910, giving a measurement of the overall efficiency of a Telefunken musical (Wien) 2 K.W. spark transmitter as 40 per cent., but it would appear that the energy loss in the antenna is included in this efficiency value (see *The Electrician*, vol. 65, p. 357, June 10, 1910).

Lastly, we may consider the overall efficiency between the transmitter and the receiver. Some measurements of this kind are recorded in M. Tissot's book, "Étude de la Résonance des Systèmes d'Antennes dans la Telegraphie sans fils." In a certain case of a plain antenna 50 metres high and 4 millimetres in diameter, on board a French battleship *Henri IV.*, corresponding with a similar antenna at a distance of 1·7 kilometres, M. Tissot shows that when the sending antenna was charged fifty times a second to a potential equal to a 5-cm. spark the mean radiation was 36 watts, or $1{\cdot}8 \times 10^7$ ergs. per spark. At a distance of 1 kilometre the energy picked up by a similar receiving antenna was 320 ergs. per spark, or 6400 ergs per second. Hence the captured energy even at this short distance was only $\frac{1}{600}$ of 1 per cent. of that sent out from the transmitter and a still smaller fraction of that given to the transmitter. M. Tissot notes the curious fact that the energy picked up by the receiving antenna is larger than that corresponding to its own surface. The figures given will, however, be sufficient to show the exceedingly small fraction of the power supplied to the transmitter which is represented by the oscillations set up in the receiving antenna by the radiotelegraphic appliances at present in use. The state of affairs is analogous to that of solar radiation. The earth only captures about 5×10^{-10} of the energy sent out from the sun, and the earth and the sun may be regarded as the receiver and transmitter in a system of short wave wireless telegraphy on a gigantic scale.

CHAPTER X

RADIOTELEPHONY

1. The Problem of Radiotelephony.—Before the invention of the methods of radiotelephony described in this chapter, attempts had been made with some degree of success to transmit articulate speech over moderate distances without the aid of a connecting wire.

In addition to methods depending upon the induction of currents between distant circuits and their conduction through the earth, a method to which the attention of Sir William Preece and Sir John Gavey was in past years particularly directed, another method was worked out based upon a peculiar property of selenium of varying its resistance under the action of light, and of the continuous-current electric arc of varying the intensity of its light when a periodic current is superimposed upon the continuous one operating the arc. This last method has been the subject of much laborious work by E. Ruhmer, of Berlin.[1]

The above methods, however, are in some respects defective. The inductive method labours under the disadvantage that the mutual induction between two circuits decreases very rapidly with the distances, varying almost inversely as the cube of the distances, and the method depending upon the use of an arc lamp is interfered with by daylight and by fog. We shall confine our attention, therefore, in this chapter to the details of the method employing electromagnetic waves which gives the greatest promise of ultimate utility, and is now generally called *radiotelephony*.

Radiotelephony consists, therefore, in the transmission to a distance of articulate speech through space without wires by means of electromagnetic waves, as distinguished from radiotelegraphy, which is the transmission of intelligence by means of arbitrary signs, whether audible or visible.

As soon as radiotelegraphy, as conducted by the methods already described in previous chapters, had made a certain progress, inventors naturally had their minds turned to the problem of the transmission of articulate speech by the same means. It soon became clear, however, that the attainment of any practical success was bound up with the invention of a transmitter for producing undamped electric radiation and upon a receiver which should be quantitative in action ; that is to say, one not merely set in operation by oscillations like a coherer, but producing an effect proportional to the amplitude of the

[1] For a detailed account of this work the reader is referred to Herr Ruhmer's book *Wireless Telephony*. English translation by Dr. Erskine-Murray.

waves incident on the receiving antenna. The oscillation detector to be used in connection with radiotelephony must, therefore, be of such a character that it is capable of varying the current through a telephonic receiver in exact correspondence with the variations of air pressure due to the speaking voice taking place in proximity to the particular telephonic transmitter employed at the sending station.

In electric telephony conducted with wires, the apparatus usually employed consists of a transmitter of the microphone type, and a receiver of the Bell or magnetic type. For instance, in the simplest form of short distance transmitter and receiver, a microphone transmitter consists of a metal diaphragm which is set in vibration by the variations of the air pressure taking place in proximity to the mouth of the speaker uttering near it articulate words. Connected to the diaphragm is some mechanism by which an imperfect contact between carbon surfaces is altered by pressure. In the ordinary type of granular carbon microphone the movements of the diaphragm due to the vibrations of the air produced by the voice are made to press together more or less small fragments of graphitic carbon contained in a shallow chamber, and so alter the electric conductivity of the mass. This variable carbon resistance N (see Fig. 1) is placed in

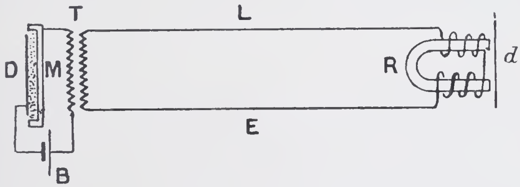


FIG. 1.

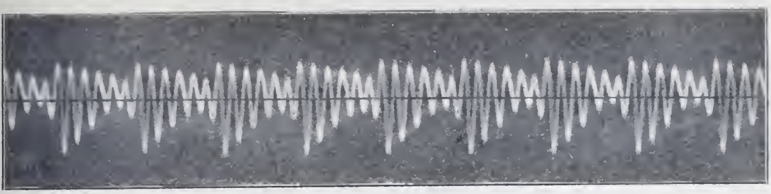
series with a few voltaic cells, V, and with the primary circuit of a small induction coil, T. One end of the secondary circuit of the induction coil is connected to one of the line wires, L, and the other to the earth or to a duplicate line wire if a complete metallic circuit is employed. At the receiving end the current in the line passes through magnetizing coils which are placed on the polar extremities of a permanent magnet, and close to these poles is held a thin flexible sheet-iron diaphragm. When the variable current passes through the magnetizing coils, the diaphragm is more or less drawn in and its vibrations therefore reproduce, and are similar to, the variations of the current in the line wire. If, then, an articulate sound is created near the diaphragm of the transmitter, there will be variations of air pressure which may be represented by the ordinates of a periodic curve. In the case of a purely musical sound this curve approximates in form to a simple sine curve, but for any sound such as a vowel sound the form of the curve will be complicated and periodic if the vowel sound is continued. In Fig. 2 are shown curves taken with a Duddell oscillograph which represent the variation of current through a telephonic circuit when the various sounds are being made against the diaphragm of the transmitter. It will be seen that these curves are periodic and yet very irregular. By

Fourier's theorem these complex curves can be resolved into the sum of a number of simple periodic curves or sine curves of different frequency and amplitude, these component sine curves differing from one another in phase. These curves, therefore, confirm von Helmholtz's celebrated synthesis of the vowel sounds. In the case of articulate sounds, variations in air pressure are non-repetitive, but they can, nevertheless, be represented by the ordinates of a single valued curve. Thus, for instance, in speaking to a phonograph the voice creates variations of air pressure in front of the speaking diaphragm and at the back of this diaphragm, or connected with it by a system of levers, is a delicate cutting tool which carves out upon the surface of the revolving plastic cylinder or disc which forms the receiving surface, a little channel or groove the bottom of which is irregular, the depth of this groove corresponding from instant to instant to the variations of air pressure produced against the diaphragm by the vocal organ. If, therefore, a section could be made of this groove and the outline at the bottom enlarged, it would present the appearance of a very irregular non-repetitive curve, each change in the ordinate of which, however, corresponds to a change in air pressure of the air in front of the diaphragm against which speech is being uttered, and which, therefore, has a vocal signification.

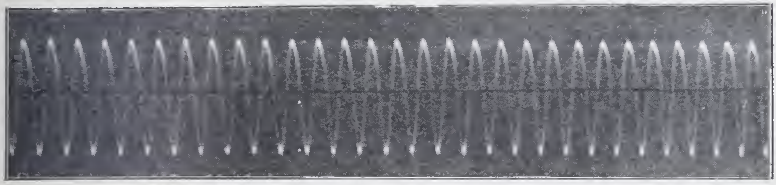
In the curves shown in Fig. 2, certain vowel sounds produced in conjunction with a consonantal sound are exhibited.

The problem of telephony is therefore to cause some other diaphragm at a distance to be moved from instant to instant in a similar manner to that of the diaphragm against which speech is being made. This receiving diaphragm will then reproduce at the distant end the same variations of air pressure as those which actuated the transmitting diaphragm, and the human ear placed in proximity to the receiver will therefore hear the speech being made at the distant place. In telephony with wires the movements of the transmitting diaphragm are made to translate themselves into corresponding variations in the strength of an electric current in the connecting wire by means of the variation in resistance which takes place when carbon surfaces are more or less pressed together, and the re-translation of this variable electric current into the movement of a receiving diaphragm is made to take place by means of the variations in the polar strength of a magnet, which take place when an electric current of varying strength circulates round these magnetic poles.

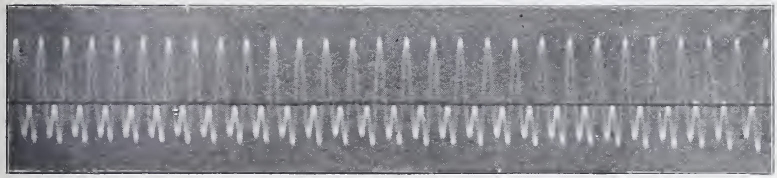
To achieve radiotelephony, we remove the interconnecting wire and substitute for it a train of electromagnetic waves passing through space. Hence the particular inventions required in order to accomplish the desired result as regards the transmitter are, to devise a mechanism capable of emitting undamped electromagnetic waves, and a mechanism capable of varying the amplitude of these waves in accordance with the variations in the air pressure taking place against the transmitting diaphragm. At the receiving end we must cause these undamped waves of variable amplitude to actuate a mechanism which shall cause them to set in vibration a receiving diaphragm, so that its displacements create aerial vibrations which reproduce in wave form those which are being made against the diaphragm of the transmitting instrument.



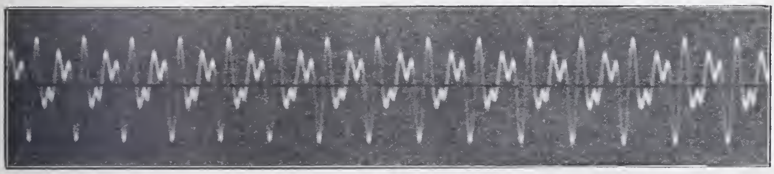
Vowel ā as in Ma.



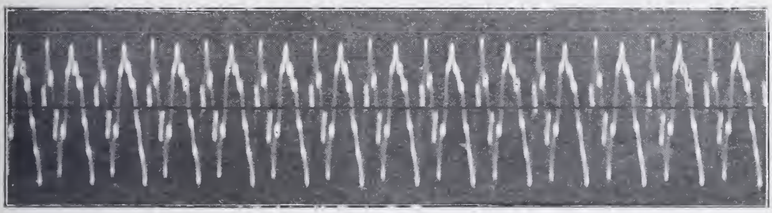
Simple Form of ōō Sound as in Coo.



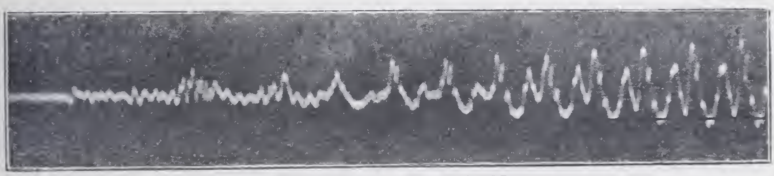
Complex Form of ōō Sound as in Coo.



Vowel ō as in Ho.



Vowel ē as in Me.



K and First Part of e as in Key.

[*By permission from " The Proceedings of the Royal Institution of Great Britain*, 1906."]

Fig. 2.—Oscillograms or Wave Forms of various Sounds taken with the Oscillograph by Mr. W. Duddell, F.R.S.

We have therefore to consider, first, the arrangements for generating the undamped electric waves in the transmitter; secondly, the means for modulating the amplitude of these waves in accordance with the wave form of articulate speech; and, thirdly, the arrangements for receiving these electric waves of variable amplitude, and causing them to affect a speaking telephone.

Sending and receiving antennæ at the two stations are requisite, as in connection with radiotelegraphy, to radiate and to absorb the electromagnetic waves. Owing to the divergence of this wave energy, and to the small fraction of the emitted power which is captured by the receiving antenna, it is necessary to modulate or control much larger currents in radiotelephony than it is in connection with telephony with wires. The difficulties still outstanding in radiotelephony are largely those of modulating large high-frequency currents by means of some form of speaking microphone as described in the following sections.

2. Methods for Generating Undamped High Frequency Oscillations for Radiotelephony.—It is now agreed that for the perfect transmission of articulate speech by electromagnetic waves an essential condition is the means of producing at the transmitting station in the sending antenna undamped or practically undamped electric oscillations. We have at this time available two fairly effective means of doing this, namely, by the use of a high-frequency alternator, or by the use of a continuous-current arc placed in a hydrocarbon atmosphere, or by a series of continuous-current arcs in air.

The alternator method has been particularly put in practice by R. A. Fessenden, and the arc method by V. Poulsen and E. Ruhmer.

An essential condition of success in the transmission of articulate speech by electromagnetic waves is that there should be no interruptions in the uniform flow of the undamped oscillations, at least not below such a frequency as forms the upper limit for audible audition. If regular vibrations are set up in the air, these are appreciated as sound by the normal ear, if they lie in frequency between about 40 and 20,000 per second. Human ears vary, however, a great deal in the value of the highest frequency which can be heard as sounds. As regards musical sounds, the highest note employed in music does not generally exceed in frequency 4000 or 5000. If, then, intermittent trains of damped waves were employed, even if the frequency of the trains were as much as 4000 or 5000, they would affect the oscillation detector at the receiving station and produce in any telephone connected with it a musical sound of high pitch which would drown out the variations of lesser frequency constituting articulate speech. Hence, if an alternator producing alternating current having a frequency within 10,000 were connected to a radiating antenna, it is probable that most persons would hear a sound in a telephone connected to an electrolytic oscillation detector in a corresponding receiving antenna. If, however, the frequency were forced up to 20,000, most persons would probably hear no sound. We may say, therefore, that to be of practical use in radiotelephony, a high-frequency alternator should give a current having a frequency of not less than 20,000, and preferably

as high as 40,000 or 50,000. It is easily seen that to attain this frequency very high speeds of revolution are necessary in the alternator armature or disc, and therefore there is a practical limit to the diameter of such a disc.

As regards driving power, the best form of motor has been found to be the De Laval steam turbine, which, in small sizes of 8 or 10-h.p., can be made to run up to 30,000 R.P.M., or 500 revolutions per second. Electric motors have, however, been constructed for the author which, for 1-h.p. size, have run up to 6000 R.P.M., and for 5-h.p. size up to 4000 R.P.M., and these speeds could easily be multiplied tenfold on a shaft by the employment of a thin and very flexible belt. The attainment of high speeds is facilitated by the use of ball or cylinder bearings and adequate lubrication, but, above all, demands very perfect balancing. In the general design of the alternator the choice lies between the inductor type of machine, in which the only revolving part is an iron disc with teeth cut on the edge, and that type of alternator with polar teeth.

The inductor type of alternator has the advantage that it is easy to balance it. Generally speaking, there is a considerable decrease in terminal voltage with increase in current taken out of the machine. Fessenden has pointed out that it is important that a high-frequency alternator should give an electromotive force-curve having a true sine form, as it is only then that resonance can be employed to multiply the electromotive force. For this reason it is necessary that there should be no iron in the armature, and as the polar teeth of the field magnet must be very narrow and close together, and not more than 2 or 3 millimetres in width, it is necessary to place all the teeth of one polarity on the same side to avoid magnetic leakage. This, then, results in the selection of the Mordey type of alternator with fixed non-iron armature and revolving fields. Fessenden has constructed such an alternator with fixed armature and revolving field having 360 poles or teeth. At a speed of 139 revolutions per second it gave a terminal electromotive force of 65 volts and an alternating current with a frequency of 50,000, the maximum output at this frequency being 300 watts. He has also constructed a high-frequency alternator directly coupled to a De Laval turbine having an electromotive force of 225 volts, a frequency of 75,000, and an output of 2·5 kw. The machine is of the double armature type with 300 coils on each, and field magnets with 150 teeth. The two air-gaps are only one-sixteenth of an inch in width, and the turbine is supplied with steam at 100 lbs. to the square inch. The attainment of a speed as high as 8000 R.P.M. in any revolving shaft or disc necessitates extremely perfect balancing, and if used on board ship special devices are necessary to obviate gyrostatic action, which would cause serious wrenching at the bearings when the ship pitches and rolls.

Turning, then, to the other method, already described, for the production of undamped oscillations by means of the electric arc in hydrocarbon atmosphere, we find that in addition to V. Poulsen, many other inventors have devoted much attention to arc generators, and applied them successfully in the transmission of speech for considerable distances over land and sea (see Fig. 3).

As the method of producing undamped oscillations by the aid of

a continuous current arc formed between a rotating carbon cathode and a cooled copper anode in hydrocarbon gas has already been fully described in Chap. I., we need only here consider the most recent modifications of the apparatus. To get rid of the necessity for cooling the box containing the electric arc with water, it is now constructed with radiator flanges so as to be air cooled, and in place of using coal gas to supply the hydrocarbon atmosphere, alcohol is introduced into the arc chamber drop by drop by means of a sight-feed lubricator controlled by a hand or electromagnetic valve. A small arc can be now employed, working with an electromotive force of 220 or 230 volts and taking a current of $1\frac{1}{2}$ or 2 amperes. It becomes, therefore,

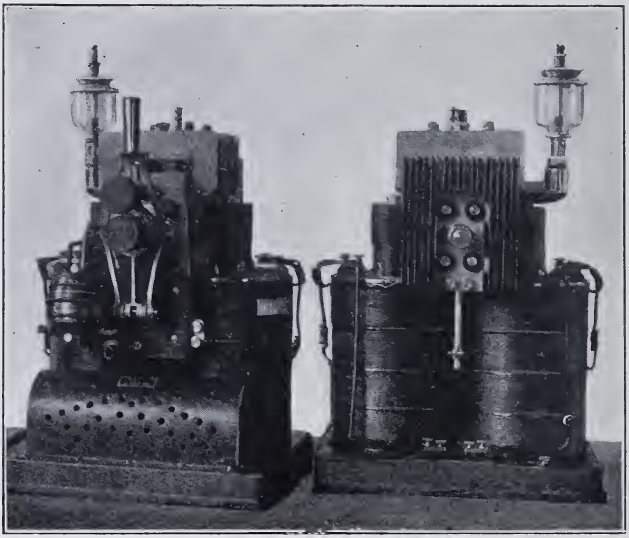


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FIG. 3.—Poulson Arc Transmitter for Radiotelephony.

quite easy to operate it off any commercial electric lighting circuit furnishing continuous current of 220 volts, and its power consumption is not more than 300 or 400 watts. The current through the arc is regulated by adjusting the distance of the carbon and copper electrodes by a screw which is hand regulated, that is to say, an assistant keeps the current through the arc constant by watching an ammeter in series with it and adjusting the screw. Apparatus has also been devised for performing this adjustment automatically. The arc is generally formed in a powerful transverse magnetic field, and the carbon is made to rotate slightly by means of clockwork or an electric motor. On the other hand, the electric arc may be made to travel round the edge of the carbon by employing a feeble radial magnetic field, and doing away therefore with the necessity for any clockwork or motor. Connected to the copper and carbon electrodes of the arc is an oscillation circuit consisting of a variable inductance

formed of a helix of wire, and a condenser of variable capacity consisting of metal plates in oil. A number of semicircular plates are fixed to an axis which can be revolved, and thus can be moved more or less in between a number of similar fixed semicircular plates which alternate with the movable ones. The two sets of plates constitute the surfaces of a condenser, and the oil with which the vessel is filled which contains the plates is the dielectric. Hence, by simply turning round a milled head on the top of the cylinder large variations of capacity can be created. Joined in series with this condenser is generally a helix of copper wire with a sliding contact, by means of which more or less inductance can be introduced. In constructing this oscillation circuit it is important that the capacity should be kept small and the inductance large. If the capacity is reckoned in electrostatic units, and the inductance in centimetres, then the ratio of these two numbers may be as 1 to 20, or even in some cases as 1 to 100. The oscillations in this circuit can be employed to induce others in another circuit to which is connected the antenna, or the antenna may be connected directly to the oscillation circuit shunted across the arc. Generally speaking, the oscillation circuit has capacity and inductance sufficient to give it an oscillation constant of anything between 5 and 50; in other words, the frequency may be anything between 1,000,000 and 100,000.

Instead of placing the arc in a strong magnetic field and enclosing it in an atmosphere of hydrogen or hydrocarbon, it has been found that good results can be obtained by the use of a number of arcs in series burning in air, or at any rate in an atmosphere deprived of oxygen. It has already been explained in Chap. I., § 14, that the characteristic curve of a continuous current arc is steeper for small currents than for large ones. If a number of electric arcs taking a small current are joined in series, and a condenser circuit possessing inductance shunted over the whole number, it is possible to arrange these arcs so as to take a small current and to have a steep characteristic curve corresponding to that current. An arrangement which has been worked out by the Gesellschaft für Drahtlose Telegraphie in Germany is as follows :—

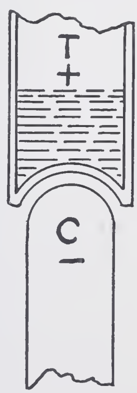

Fig. 4.

A copper tube has a concave bottom fixed to it, and this tube is filled with water to keep it cool. The tube forms the positive terminal of the arc. The negative terminal is formed by a solid carbon rod C, and the arc is struck in the cavity formed by the recessed end of the copper tube T (see Fig. 4). Six or twelve such tubes may be arranged in a row or two rows, and a number of carbon rods attached to a lever with an adjustment such that each carbon rod can be moved up or down independently at pleasure, or the whole number moved together slightly downwards by means of a touch on a single lever (see Fig. 5). By this mechanism all the carbons can be put in contact with the concave copper anodes, and then by one movement all the arcs are struck together. The carbon rods and copper cylinders are connected up in series, so that a current passing through them all forms an arc between the carbon tips and

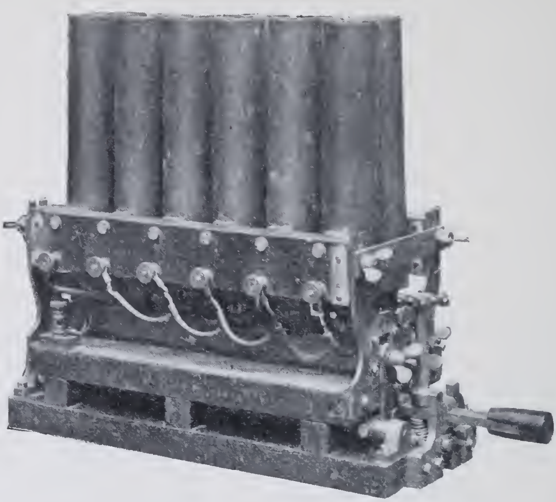

FIG. 5.—Multiple Arc Apparatus for the production of persistent Oscillations.

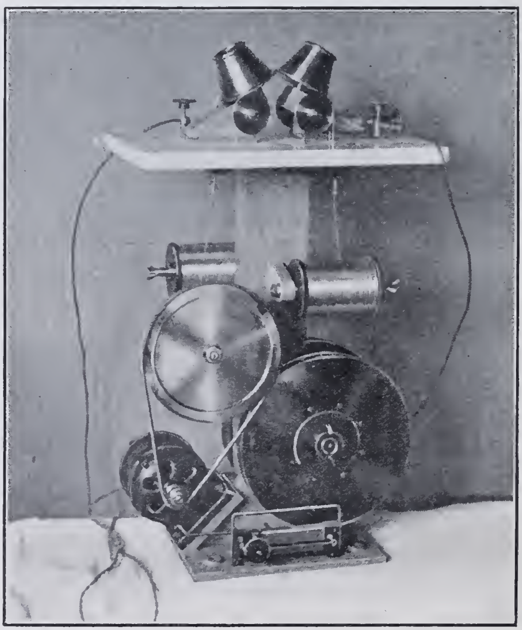

FIG. 6.—Ruhmer's Arc Apparatus for producing persistent Oscillations by means of a High-tension Arc between Aluminium Electrodes.

the concave copper roof above it, and these six arcs are controlled simultaneously.

In place of a number of carbon-copper arcs in series, E. Ruhmer has found it possible to use a single arc produced by a high-tension continuous current between aluminium wires. The arrangement of his arc apparatus is shown in Fig. 6. Two bobbins of square-sectioned aluminium wire are provided, and these wires are caused to travel slowly over two insulated pulleys in such fashion that the wires at one place are separated by a few millimetres. These wires are connected to a series of secondary cells giving a voltage of 2000 volts or upwards. Between these wires a high-tension aluminium arc is formed. If this arc is shunted by a condenser and inductance, then in the latter circuit persistent or undamped electric oscillations are set up. These can be employed to create other oscillations by induction in a coupled antenna, and the antenna oscillation modulated by a microphone.

In this condenser circuit the capacity must be relatively small and the inductance large. Fig. 7 shows the complete installation of a multiple arc apparatus for radiotelephony as employed by the Telefunken Company (Gesellschaft für Drahtlose Telegraphie), in which carbon-copper electric arcs in series are thus used as a generator for the production of undamped oscillations.

Another form of transmitting arrangement has been described by Fessenden (see U.S.A. patent specification, No. 793,649, March 30, 1905), in which a high-tension, continuous-current dynamo or else a number of such machines in series generate a continuous voltage. This current passes through a regulating resistance, and also across a spark gap formed between a metal point carried at the back of a telephone diaphragm and a rapidly revolving disc carried on the shaft of a motor. The spark gap is also shunted by an oscillatory circuit consisting of a capacity and an inductance, and an antenna syntonized to it is connected to the circuit. The precise operation of the apparatus is not described, but it may be assumed that the arrangement operates somewhat in the manner of a continuous-current arc apparatus (see Chap. I. § 14), and that a series of discharges passes across the spark gap, and that articulate sounds spoken to the diaphragm, by varying the spark length, vary also the frequency of these discharges and therefore the amplitude of the radiated waves. No arrangement, however, can possibly give good results as a transmitter in radiotelephony in which the waves are not either perfectly undamped or else consist of wave trains succeeding each other at a rate greater than 20,000 or 30,000 per second. Many attempts have been made to utilize for this purpose the phenomenon of multiple discharges of the condenser, by employing a very short spark gap. Thus, Professor Q. Majorana has produced condenser discharges succeeding each other at the rate of 10,000 per second by the use of a very short spark gap and high impressed voltage, and inserting a large inductance in series with the source of electromotive force. Unless, however, the trains of oscillations succeed each other at a greater rate than 20,000 per second, the intermittances are heard in the receiving telephone as a continuous sound.

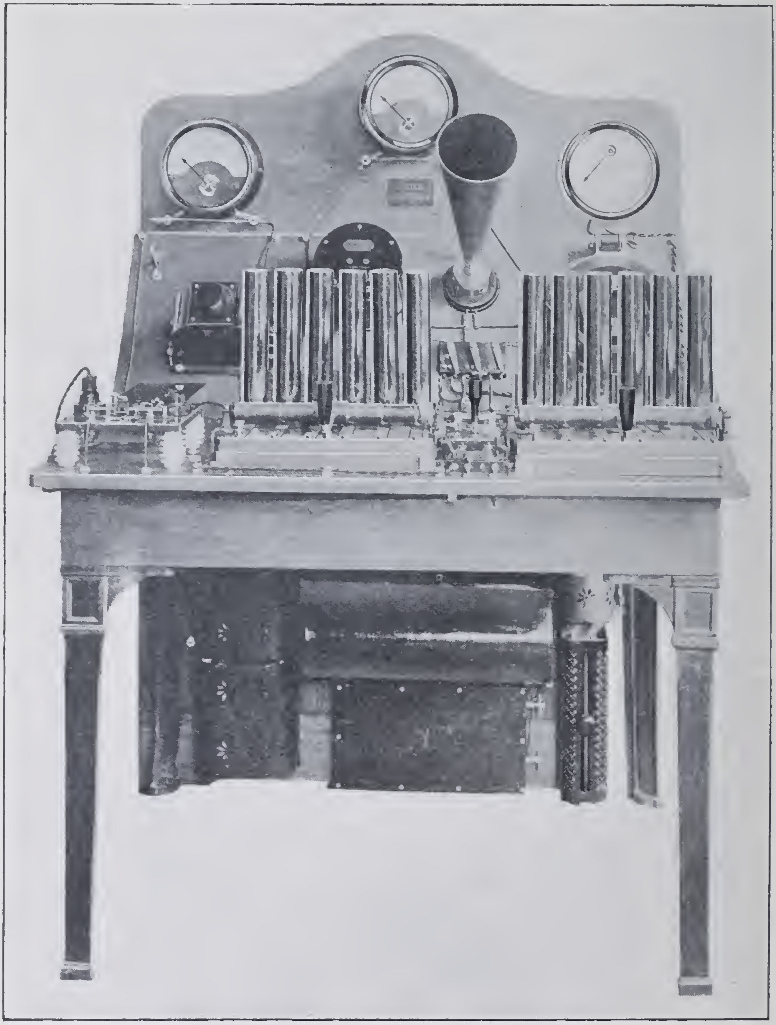

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FIG. 7.—Telefunken Multiple Arc Transmitting Apparatus for Radiotelephony.

Another arrangement due to Fessenden (see U.S.A. patent specification, No. 932,111, December 14, 1905) employs what he calls a condenser dynamo. If we imagine two stellate discs placed parallel to one another, one of them connected with the positive pole of a battery or high-tension continuous-current dynamo, and the other with the negative, the arrangement forms a condenser of small capacity. If one of these discs revolves, or both revolve in opposite directions, then when the vanes are opposite to one another the capacity of this condenser will be a maximum, and when they are staggered or interspaced the capacity will be a minimum. Hence an intermittent current from the battery flows into this condenser of periodically varying capacity, and is equivalent to a series of undamped oscillations. By means of a suitable oscillation transformer this variable current may be transformed up in voltage into an alternating current of high frequency and high voltage. By employing a sufficiently large number of sectors in the revolving condenser plates and a high-speed periodic currents of a frequency of 100,000 can be obtained.

By any of the above means we are enabled to establish in an antenna undamped or persistent oscillations and to radiate corresponding trains of waves. We may set up these oscillations in a circuit having inductance and capacity, and connect the properly syntonized antenna with this circuit by loose coupling, or we may connect the antenna itself directly to this oscillation circuit, or else insert the generator of undamped oscillations in the antenna circuit itself. If the antenna is inductively coupled to a reservoir circuit it is necessary to employ somewhat loose coupling to avoid dividing the energy between waves of two wave lengths.

3. Microphonic Control of Electric Oscillations.—In order to conduct radiotelephony, we have then to control the amplitude of the electric waves emitted by the antenna in such a manner that this amplitude may vary in exactly the same way and proportionately to the change of air pressure at any point near the mouth of the person uttering articulate speech. This is best done by the insertion of a speaking microphone in the condenser shunt circuit, or else in a circuit inductively connected with it. Such a speaking microphone consists of a shallow metal chamber closed by a flexible metal diaphragm which is insulated from the metal chamber, the space between the diaphragm and the solid back containing carbon granules which are more or less pressed together by the vibrations of the diaphragm. Hence when speech is made against the mouthpiece terminating on the diaphragm, the aerial vibrations set up similar vibrations in the diaphragm, and these movements, by pressing more or less the carbon granules, vary the resistance of the carbon included between the diaphragm and the solid back. It is found, however, that a single microphone transmitter cannot be operated satisfactorily with a current exceeding half an ampere, or at most one ampere, passing through it, nor if inserted in a circuit in which rupture of the circuit brings into operation large potential differences between the points at which rupture is made. Hence if the microphone is inserted in a condenser circuit, it must be put at a central or symmetrical point, that is, at a place which has a node of potential,

or otherwise there is a tendency to produce sparking between the carbon contacts. The microphone must therefore be inserted in the earth wire of the antenna if it is used in the antenna circuit, or if it is used in any tertiary circuit, it must be placed at a symmetrical point which has a node of potential.

If the current in the circuit is larger than about half an ampere, it is necessary to employ a number of microphones in parallel, and these may be arranged at the ends of tubes which are operated by a common mouthpiece (see Fig. 8) so that the diaphragms are all affected together, and the carbon resistances can then be connected in parallel, or otherwise they may be connected, if desired, in series.

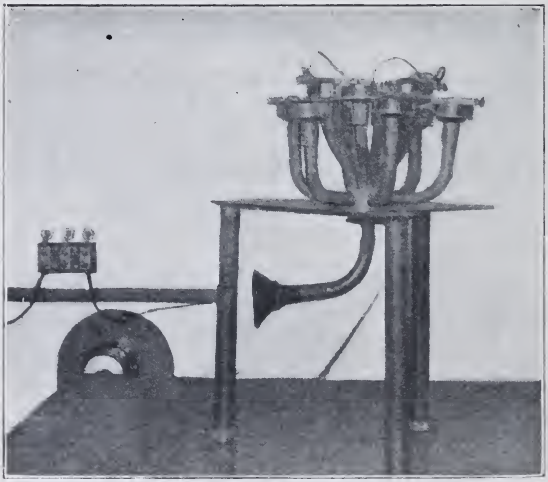

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Fig. 8.—Multiple Microphone.

In the arrangements adopted by Poulsen, this microphone transmitter, or variable resistance, is inserted either in the condenser shunt circuit of the arc, or else in a tertiary circuit closely connected thereto (see Fig. 9). When speech is uttered against the microphones it varies the resistance of this microphone circuit, and therefore alters the resistance of the condenser circuit slightly, and thus affects the current in the sending antenna. Words spoken to the mouthpiece, therefore, produce an effect upon the amplitude of the emitted electric waves, and these amplitudes are, so to speak, moulded into the form of speech; that is to say, made to vary as the ordinates of a wave curve representing the changes of air pressure taking place near the mouthpiece of the transmitter. In some cases the microphone resistance may be inserted in the circuit of the electric arc itself and operate directly upon the continuous current affecting the arc. In this case the variation of the condenser current, and also of the amplitude of the waves radiated from the antenna, takes place in the same manner as the variations in the arc current produced by

the changes in resistance of the microphone and of the action of the articulate sounds. Or, again, the microphone may be inserted as a shunt to the secondary circuit of the oscillation transformer connecting the antenna to the condenser circuit, so that the current into the antenna is more or less shunted to earth.

Finally, the microphone may be inserted in the earth connection of the antenna, so as to vary the current flowing into the antenna itself, and therefore the intensity of the radiated waves.

Another plan that has been suggested is to employ a condenser telephone consisting of two plates of metal near one another, one of which constitutes the diaphragm against which speech is made, so that by the vibrations of this diaphragm under the operation of the voice, the plates are more or less approximated, and their electrostatic capacity varied. If this condenser transmitter is joined in

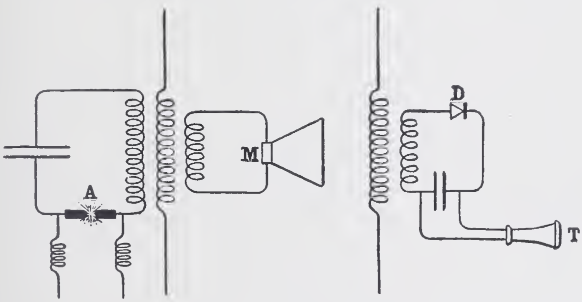

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FIG. 9.—Scheme of Circuits of Transmitter and Receiver for Radiotelephony.

parallel with the main condenser in the shunt circuit of the arc, speech made against it, by altering its capacity more or less, throws the condenser circuit out of tune with the antenna circuit, and therefore varies the intensity of the emitted waves. By any of these methods the train of undamped waves emitted by the antenna has its amplitude varied in accordance with the wave form of the speech made to the microphone, and these waves when incident on the receiving antenna are made to reproduce sound by the arrangements employed in the receiving circuit.

The difficulty that has usually been experienced in constructing a microphone for use in connection with the transmitter of radiotelephonic apparatus is that with the ordinary carbon microphone only a small current, not more than about half an ampere, and a small voltage, not more than a few volts, can be employed with the carbon microphone without producing sparking or objectionable heating. Hence the attention of inventors has been directed to improving the microphone for this purpose. One of the most interesting of these attempts is that by Professor Majorana of Rome, who has devised a liquid microphone for this purpose. These conditions have been fulfilled by taking advantage of the property of fluid jets. If

a stream of water to which a little acid has been added flows from a suitably constructed jet under pressure it divides itself into drops which follow each other at practically constant intervals. This can be verified by throwing the shadow of the jet upon a screen and illuminating it by means of intermittent flashes of light. When these flashes of light come at intervals corresponding to the time required for one drop to move into the position of the drop next in front, the shadow of the jet will appear stationary upon the screen and be seen broken up into separate drops. If these drops fall on a level surface at right angles to their direction, a layer of liquid is formed upon that surface, the thickness depending upon the frequency with which the drops strike the surface. Professor Majorana has constructed his liquid microphone on the following principles:—

A mouthpiece of the usual shape and a diaphragm which can be set in vibration by the speaking voice are connected by means of a

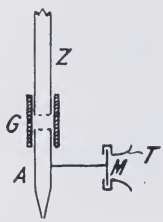

Fig. 10.

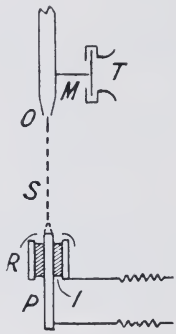

Fig. 11.

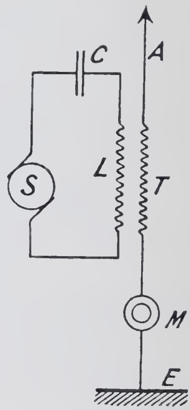

Fig. 12.

Details of Majorana's Liquid Microphone.

rigid attachment with a flexible tube out of which the liquid flows, so that vibrations imposed upon the diaphragm set up vibrations in the stream of liquid issuing from the jet (see Fig. 10). This liquid falls upon a collector, which consists of a circular pin or cylinder of platinum surrounded by a cylinder of insulating material, and this again by another outer cylinder of platinum. The jet therefore covers the end of this compound cylinder with a layer of conducting liquid which connects the two platinum electrodes, interposing a resistance depending upon its thickness (see Fig. 11). Hence if the liquid jet is made to vibrate, and the frequency of the drops into which it breaks altered, the thickness of the film of liquid is varied, and its resistance is therefore changed in the same manner. A comparatively large current can be passed through this film of liquid from one platinum cylinder to the other owing to the fact that the liquid being continually removed cannot be overheated, and owing to the high specific resistance of the fluid, a considerable voltage can

be applied to the film. The liquid film is then inserted between the antenna and the earth (see Fig. 12) in the arrangement already described, and the vibrations of the speaking voice operating on the jet of liquid are thus made to affect the thickness and therefore resistance of the liquid film, and thus to vary the intensity of the oscillations in the antenna and therefore the amplitude of the radiated waves.

A form of multiple microphone and also a duplex carbon microphone have also been invented by Ernest Ruhmer, in which special arrangements are made to prevent the contact between the carbon granules and the diaphragm from being interrupted so as to give rise to sparking. There are special difficulties in connection with the design of a suitable microphone for modulating a high-frequency current of 5 to 10 amperes or more. The variable resistance, generally carbon, must not heat or break contact so as to spark, and must respond in resistance variation accurately to the movements of the diaphragm. A form which presents some advantages is that of A. F. Collins (see *The Electrician*, vol. 65, p. 472, July 1, 1910).

In this microphone the carbon granules are contained in a cell the opposite walls of which form the diaphragms set in vibration by the air motion. The carbon granules are placed between two polished carbon surfaces attached to the backs of these diagrams, and a mouthpiece leading into a bifurcated tube enables the variations of air pressure to be communicated simultaneously to the two diaphragms, which thus move in and out together. The granules are thus squeezed between the diaphragms when they move in together. Fig. 13 shows a section, and Fig. 14 an outside view, of this transmitter. A number of these microphones may be joined to one mouthpiece, their resistances being arranged either in series or in parallel, as in Fig. 15.

The variable carbon resistance can also be water-cooled. In this manner a microphonic variable resistance can be constructed which can carry an antenna current of 8 or 10 amperes, and yet modulate this current sufficiently to transmit speech by radiotelephony.

4. Receiving Arrangements in Radiotelephony.—Assuming that a transmitting station is sending out undamped waves which are being moulded into speech form by means of a microphone controlled as already described, these waves may be absorbed by a properly syntonized receiving antenna tuned to the wave length employed, and by suitable arrangements can be made to affect a telephone so as to translate back the oscillations of constant frequency but variable amplitude induced in the receiving antenna into articulate sounds. For this purpose it is necessary to employ in the receiving circuit an oscillation detector which is quantitative, that is, not merely affected by oscillations, but affected to some extent proportionately to their amplitude. Thus, for example, a coherer or oscillation detector of the imperfect-contact type will be of no use, because it is only affected by a certain alternating voltage, and is at once affected almost to the full degree when that voltage reaches a certain limit. Several forms of oscillation detector, already described in Chap. VI., are very suitable for radiotelephonic reception, such as Fessenden's electrolytic detector, the author's glow-lamp or ionized gas-detector, the thermoelectric detectors, and the crystal detectors

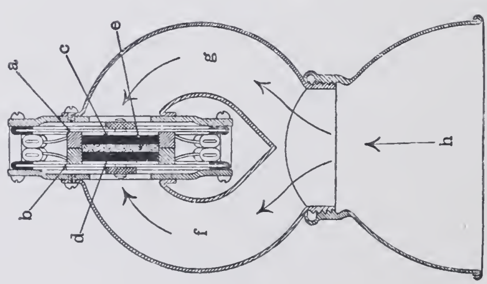

FIG. 13.—Collins Microphone for Radiotelephony.

FIG. 14.—Water-cooled Collins Microphone.

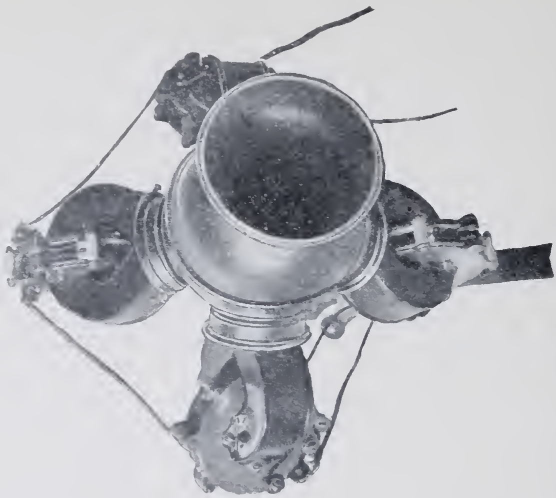

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FIG. 15.—Collins Multiplex Microphone for Radiotelegraphy.

of Dunwoody and Pierce. Thus, for instance, if a receiving circuit is constructed by inductively coupling the receiving antenna to another oscillation circuit comprising a condenser and inductance properly syntonized to the antenna circuit, and if an electrolytic detector in series with a telephone and a shunted local cell is put across the terminals of the condenser, then oscillations passing through the electrolytic detector will not only alter its apparent electric resistance, but alter it in some sense proportionately to their intensity, and hence if undamped waves are falling upon the antenna of constant wave length and varying amplitude, a corresponding variation in the apparent resistance of the electrolytic detector will take place, and therefore a corresponding variation in the currents through the telephone. The telephone diaphragm, therefore, emits a sound which corresponds with the fluctuation in the amplitude of the incident waves, and it therefore reproduces a speech made against the diaphragm of the transmitting microphone.

Fessenden makes use of a form of telephone he calls a "heterodyne" receiver. It consists of a pair of coils of wire, one of which is wound round an iron wire core, and the other attached to a mica diaphragm held near the core. The last-named coil is traversed by the current in the receiving antenna, and the first by a local current of the same frequency as that of the transmitter. There is, therefore, a mechanical force between the two coils which varies with every variation of the current in the receiving antenna. The diaphragm, therefore, reproduces the sounds which are made against the diaphragm of the microphone in the transmitting circuit.

In the same manner crystal detectors, which rectify the oscillations in the condenser circuit or the potential difference of the terminals of the condenser, may be used as receiving detectors in radiotelephony. Likewise, also, the glow lamp detector or ionized gas detector invented by the author may be used for the same purpose. This last detector has been a very favourite one with inventors of radiotelegraphic systems, having been employed by Lee de Forest and also by Q. Majorana in their experiments.

5. **Achievements of Radiotelephony**.—In this combined radiotelephonic transmitter and receiver we have then a wonderful transformation of energy. The variations of air pressure made by the speaking voice against the diaphragm of the transmitter microphone produce corresponding variations in its resistance. This again varies in the same manner the intensity of the electric oscillations in the oscillation circuit connected with the arc or alternator, and also the oscillations in the antenna. Electromagnetic waves are then emitted, the amplitude of which is changing in the same manner. A small fraction of the energy of these waves is captured by the receiving antenna, and oscillations set up therefore in the receiving condenser circuit, the amplitude of which varies in the same manner as that of the incident waves, and these acting on the particular detector coupled to the telephone reproduce movements in the receiving telephone diaphragm which imitate those made by the diaphragm of the transmitting microphone. Although this operation is complicated, nevertheless it has been so far perfected that articulate speech can now be transmitted over a hundred miles or more by these methods.

The picture in Fig. 16 shows the complete arrangements for employing the Poulsen arc as a radiotelephonic transmitter, and the

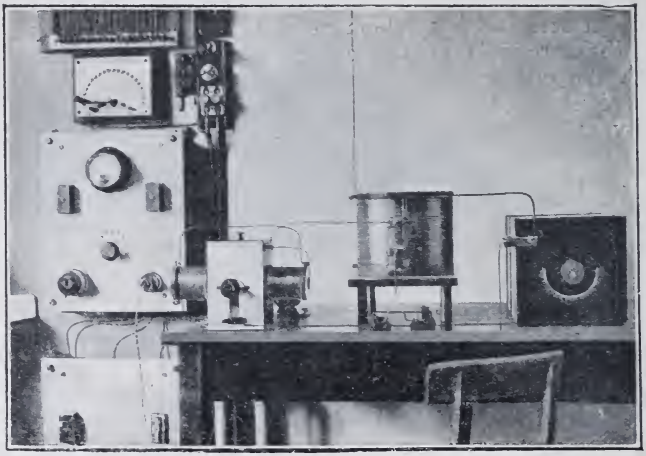

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FIG. 16.—General View of the Poulsen Transmitting Apparatus for Radiotelephony.

diagram in Fig. 17 shows the receiving arrangements made as described. By these methods Poulsen succeeded in transmitting

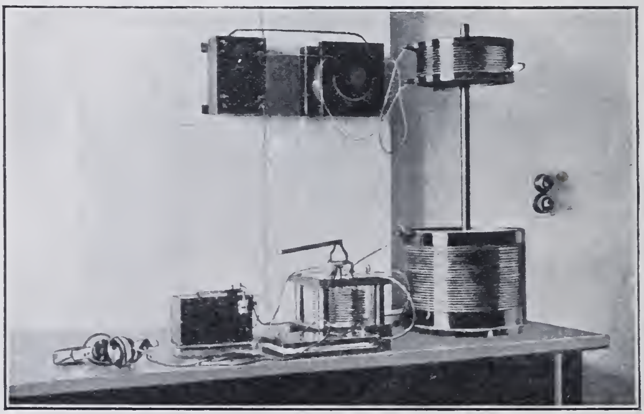

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FIG. 17.—Poulsen Receiving Apparatus for Radiotelephony.

articulate speech from Berlin to Copenhagen, a distance of 290 miles, and also from Lyngby to Esbjerg, a distance of 170 miles.

Fessenden states he has conducted radiotelephonic communication between Brant Rock and New York, a distance of 200 miles,

using 1 kw. steam turbine driven alternator, giving alternating currents of a frequency from eighty to a hundred thousand at 150 volts, and a disc armature of a resistance of 6 ohms, and a field exciting current of 5 amperes. Using a transmitting antenna 200 feet high at New York, and the Atlantic Tower, 400 feet high, at Brant Rock, an expenditure of 200 watts in the antenna was required to cover 200 miles. He also made successful demonstrations in 1906 between Brant Rock and Plymouth, Mass., a distance of 11 miles, in which speech was transmitted satisfactorily to telephone experts who were present. For a detailed account of Fessenden's work in Radiotelegraphy up to the beginning of 1907, the reader may be referred to a series of articles by him in the *Electrical Review* for February 15, 22, March 1, 15, 1907.

In 1908, similar experiments were made by Professor Majorana in Italy, between Monte Mario and Porto Danzig, a distance of 60 kilometres. In France, Lieutenants Colin and Jeanne, and Chief Engineer Mercier, achieved the distinction of transmitting speech radiotelephonically from the Eiffel Tower in Paris to Dieppe, and musical sounds from Paris to the Coast of Finisterre, a distance of 310 miles.

At a later date, by utilizing his own liquid microphone and the glow lamp oscillation detector invented by the Author, Professor Majorana has succeeded in telephoning without wires over a distance of 260 miles between Rome and the coast of Sicily.

Although, therefore, wireless telephony has not attained the range reached by wireless telegraphy, nevertheless there is evidence that it has been conducted over distances of 200 miles or so with considerable success. One feature of importance in connection with radiotelephony is that there is no distortion of the wave form with distance. In ordinary telephony with wires, this distortion, which is specially marked in the case of circuits having large capacity, such as submarine cables, and the distorting power of the circuit impose a very serious limit upon the range of telephony. Briefly speaking, the reason for this is as follows :—

If we have a conductor with resistance R per unit of length, capacity C per unit of length, inductance L per unit of length, and dielectric conductance K per unit of length, then from the fundamental equations for the propagation of electrical disturbance along such a circuit (see Chap. IV. § 1), it can be shown that the velocity of propagation of a periodic electric disturbance along the cable is a function of the frequency, the greater the frequency the less being the velocity of propagation. When articulate speech is being made against a telephone diaphragm, we have already seen that the wave form representing that articulate sound is a complex single valued curve, which in accordance with the theorem of Fourier can be analyzed into the sum of a number of simple constituent sine curves of different amplitudes differing in phase. These different harmonic constituents are propagated through the cable with different velocities and attenuated at different rates, so that when they are synthesized at the other end by the receiving telephone and the ear, the wave form which is reproduced is not an exact copy of the sound originally transmitted. In other words, we may say that the received sound is

a caricature of the sound made in the transmitting microphone. If the distortion is not too great, the ear at the receiving telephone is able to reconstruct or guess the sound at the other end creating it, just as we can recognize the original in a caricature of the human face if the caricaturing is confined within certain limits. Or to use another simile, in ordinary handwriting probably no single letter is quite correctly formed. If, however, the departure from perfect correctness is not too great, practice enables us to guess the word which is signified. The ear is therefore in this way able to recognize as a certain articulate sound, a sound which is not precisely like it. If, however, the distortion of the wave form has proceeded beyond certain limits, the ear is no longer able to recognize the origin of the sound heard. Hence a serious limit is imposed upon telephony through the ordinary submarine cable.

It can be shown from the theory of such a cable, that if the relation between the four constant quantities R, L, C, and K is such that if $\frac{R}{L}=\frac{K}{C}$ then the cable will possess no distortion. In most ordinary cables the inductance is too small to fulfil this relation, but by the addition of inductance coils inserted at certain regular intervals in the cable, Pupin has been able to improve considerably telephonic speech through cables and long aerial lines. Such a cable is called a *loaded cable*. In the case, however, of wave transmission through the æther there is no distortion, because electromagnetic waves of all wave lengths travel through the æther at precisely the same speed, namely with the velocity of light. Accordingly, whatever may be the wave form of the wave which leaves the transmitting antenna, it will always preserve that same wave form although it may be attenuated or weakened by the diffusion of the energy over a large area. Accordingly, the difficulty caused by distortion in telephony through conductive circuits does not exist in the case of radiotelephony. The chief difficulty which presents itself in connection with radiotelephony is that of modulating the amplitude of oscillations of sufficient intensity in the sending antenna by means of some suitable form of microphone. By means of the continuous current arc, or a high frequency alternator, we can create in the sending antenna undamped oscillations of considerable amplitude, and it remains then only to devise convenient forms of microphone for modulating this amplitude in accordance with the wave form of articulate speech, to be able to accomplish radiotelephony over any distance over which radiotelegraphy is possible. Owing to the difficulties of producing steady, maintained, persistent oscillations by means of the electric arc, and the want of a simple and manageable microphone, radiotelephony has hardly yet passed beyond the experimental stage; but these difficulties may be overcome, and there is therefore nothing inherently impossible in the suggestion that we may one day be able to speak across the Atlantic by radiotelephony. Even if this is not accomplished, it is possible that radiotelephony may become as widely employed as radiotelegraphy is to-day in communication between ships and the shore; but at the present time (1910) all that can be said is that it has reached a stage of development comparable with that of radiotelegraphy in 1900, and that the

interesting problems in connection with it will doubtless continue to attract the attention of experimentalists and inventors until the apparatus required is so simplified as to be capable of being commercially employed.

It cannot be denied, however, that the earlier promises of radiotelegraphy have not been altogether fulfilled. This is undoubtedly due to the difficulties in working the electric arc generator without interruptions, and however well it may operate in skilled hands or on single occasions, radiotelegraphy can never become a commercial and widely used means of communication until a simple and easily managed means of producing persistent oscillations is obtained. In short, the high-frequency alternator is too expensive and the arc method too uncertain to afford a thoroughly satisfactory basis for operating commercial radiotelegraphy at the present time.

APPENDIX I

WIRELESS TELEGRAPHY ACT OF GREAT BRITAIN, 1904 (4 Edw. VII.).

An Act to provide for the Regulation of Wireless Telegraphy.

[August 15, 1904.

Be it enacted by the King's most Excellent Majesty, by and with the advice and consent of the Lords Spiritual and Temporal and Commons, in this present Parliament assembled, and by the authority of the same, as follows:—

1.—(i.) A person shall not establish any wireless telegraph station, or instal or work any apparatus for wireless telegraphy, in any place or on board any British ship except under and in accordance with a licence granted in that behalf by the Postmaster-General.

(ii.) Every such licence shall be in such form and for such period as the Postmaster-General may determine, and shall contain the terms, conditions, and restrictions on and subject to which the licence is granted, and any such licence may include two or more stations, places or ships.

(iii.) If any person establishes a wireless telegraph station without a licence in that behalf, or instals or works any apparatus for wireless telegraphy without a licence in that behalf, he shall be guilty of a misdemeanour and be liable, on conviction under the Summary Jurisdiction Acts, to a penalty not exceeding ten pounds, and on conviction on indictment to a fine not exceeding one hundred pounds, or to imprisonment, with or without hard labour, for a term not exceeding twelve months, and in either case be liable to forfeit any apparatus for wireless telegraphy installed or worked without a licence, but no proceedings shall be taken against any person under this Act except by order of the Postmaster-General, the Admiralty, the Army Council, or the Board of Trade.

(iv.) If a justice of the peace is satisfied by information on oath that there is reasonable ground for supposing that a wireless telegraph station has been established without a licence in that behalf, or that any apparatus for wireless telegraphy has been installed or worked in any place or on board any ship within his jurisdiction without a licence in that behalf, he may grant a search warrant to any police officer or any officer appointed in that behalf by the

Postmaster-General, the Admiralty, the Army Council, or the Board of Trade and named in the warrant, and a warrant so granted shall authorize the officer named therein to enter and inspect the station, place or ship, and to seize any apparatus which appears to him to be used, or intended to be used, for wireless telegraphy therein.

(v.) Sections six hundred and eighty-four, six hundred and eighty-five, and six hundred and eighty-six of the Merchant Shipping Act, 1894 (which relate to the jurisdiction of courts and justices), and section six hundred and ninety-three of the same Act (which relates to distress for sums ordered to be paid by masters and owners of ships), shall apply to the jurisdiction of courts and justices in respect of ships, and to distress under this Act.

(vi.) The Postmaster-General may make regulations for prescribing the form and manner in which applications for licences under this Act are to be made, and, with the consent of the Treasury, the fees payable on the grant of any such licence.

(vii.) The expression "wireless telegraphy" means any system of communication by telegraph as defined in the Telegraph Acts, 1863 to 1904, without the aid of any wire connecting the points from and at which the messages or other communications are sent and received: Provided that nothing in this Act shall prevent any person from making or using electrical apparatus for actuating machinery or for any purpose other than the transmission of messages.

2.—(i.) Where the applicant for a licence proves to the satisfaction of the Postmaster-General that the sole object of obtaining the licence is to enable him to conduct experiments in wireless telegraphy, a licence for that purpose shall be granted, subject to such special terms, conditions, and restrictions as the Postmaster-General may think proper, but shall not be subject to any rent or royalty.

(ii.) Where an applicant for a licence satisfies the Postmaster-General that a wireless telegraph station is to be used solely for the transmission of telegrams which are within the first or second exception from the exclusive privilege of transmitting telegrams conferred upon the Postmaster-General by the Telegraph Act, 1869, a licence for that purpose, if granted, shall not be subject to any rent or royalty.

(iii.) It shall be lawful for the Postmaster-General, due regard being had to the maintenance and exercise of effective control over wireless telegraphy, to grant special licences at reduced terms for the establishment and working of wireless telegraph stations to be used exclusively for the transmission within the United Kingdom of news to public registered newspapers. A schedule of all reduced rents or royalties imposed by any special licences shall be laid before both Houses of Parliament within fourteen days of the commencement of the session next succeeding the grant of any such licences.

3.—(i.) This Act may be cited as the Wireless Telegraphy Act, 1904, and may be cited with the Telegraph Acts, 1863 to 1904.

(ii.) This Act shall extend to the whole of the British Islands and to all British ships in the territorial waters abutting on the coast of the British Islands, and the Royal Courts of the Channel Islands shall register this Act accordingly.

(iii.) His Majesty in Council may order that this Act shall, subject

to any conditions, exceptions, and qualifications contained in the order, apply during the continuance of the order to British ships whilst on the high seas.

(iv.) A person shall not work any apparatus for wireless telegraphy installed on a foreign ship whilst that ship is in territorial waters otherwise than in accordance with regulations made in that behalf by the Postmaster-General, and the Postmaster-General may, by any such regulations, impose penalties recoverable summarily for the breach of any such regulations not exceeding ten pounds for each offence, and may provide for the forfeiture on any such breach of any apparatus for wireless telegraphy installed or worked on such ship. Save as aforesaid, nothing in this Act shall apply to the working of apparatus for wireless telegraphy installed on any foreign ship.

4. In the application of this Act to Scotland the expression "misdemeanour" means crime and offence.

5. In the application of this Act to the Channel Islands and the Isle of Man—

(i.) The lieutenant-governor of the Island of Jersey or the Island of Guernsey, and the governor, lieutenant-governor, or deputy-governor of the Isle of Man, as the case may require, shall be substituted for the Board of Trade:

(ii.) Offences may be prosecuted, fines recovered, proceedings taken, and search warrants issued in such courts and in such manner as may for the time being be provided in the Channel Islands and the Isle of Man by law, or, if no express provision is made, then in and before the courts and in the manner in which the like offences, fines, proceedings, and warrants may be prosecuted, recovered, taken, or issued therein by law, or as near thereto as circumstances admit, and the bailiff or his lieutenant or any jurat of the Royal Court in the Island of Jersey or the Island of Guernsey, and the judge or any jurat of the Court of Alderney, and the high bailiff or two justices of the peace in the Isle of Man, shall respectively be substituted for a justice of the peace.

6. This Act shall continue in force until the thirty-first day of July nineteen hundred and six, and no longer unless Parliament otherwise determines.

In February, 1906, a Bill was introduced into the House of Commons by Mr. Sidney Buxton, the Postmaster-General, to continue in force the Wireless Telegraph Act of 1904 for a further six years.

APPENDIX II

The following is a translation of the French Text of the International Radiotelegraphic Convention, the Additional Engagement, Final Protocol, and Service Regulations annexed to the International Radiotelegraphic Convention, which is taken by kind permission and special arrangement from the complete translation of the *Proceedings* of the International Radiotelegraphic Conference of Berlin of 1906, made by Mr. G. R. Neilson, of the Eastern Telegraph Company, officially accepted by H.M. Postmaster-General, and published by the Electrician Printing and Publishing Company, Limited, of Salisbury Court, Fleet Street, London, E.C. This translation is copyright, and is published here by special arrangement with the Translator.

International Radiotelegraphic Convention concluded between the United States of America, the Argentine Republic, Austria Hungary, Belgium, Brazil, Bulgaria, Chili, Denmark, France, Germany, Great Britain, Greece, Italy, Japan, Mexico, Monaco, the Netherlands, Norway, Persia, Portugal, Roumania, Russia, Spain, Sweden, Turkey, and Uruguay.

The undersigned Plenipotentiaries of the Governments of the countries enumerated above, being assembled in conference at Berlin, have, by common consent and subject to ratification, agreed to the following Convention :—

Article 1.

The High Contracting Parties undertake to apply the provisions of the present Convention at all radiotelegraph stations—coast stations and ship stations—open for the service of public correspondence between the land and ships at sea which are established or worked by the Contracting Parties.

They undertake, moreover, to impose the observance of these provisions upon private enterprises authorized either to establish or work radiotelegraph coast stations open for the service of public correspondence between the land and ships at sea, or to establish or work radiotelegraphic stations, whether open for public correspondence or not, on board ships which carry their flag.

Article 2.

The term " coast station " means any radiotelegraph station which is established on land or on board a ship permanently moored,

and which is used for the exchange of correspondence with ships at sea.

The term "ship station" means any radiotelegraph station established on board a ship which is not permanently moored.

Article 3.

Coast stations and ship stations are bound to exchange radiotelegrams reciprocally without regard to the particular system of radiotelegraphy adopted by these stations.

Article 4.

Notwithstanding the provisions of Article 3, a station may be appropriated to a service of public correspondence of a restricted character, determined by the object of the correspondence, or by other circumstances independent of the system employed.

Article 5.

Each of the High Contracting Parties undertakes to cause its coast stations to be connected with the telegraph system by means of special wires, or at least to take such other measures as will ensure an expeditious exchange of traffic between the coast stations and the telegraph system.

Article 6.

The High Contracting Parties shall acquaint one another mutually with the names of the coast stations and ship stations indicated in Article 1, as well as with all such particulars proper for facilitating and accelerating the exchange of radiotelegrams, as shall be specified in the regulations.

Article 7.

Each of the High Contracting Parties reserves the right of prescribing or permitting the establishment and working, at the stations indicated in Article 1—independently of the installation of which particulars are published in accordance with Article 6—of other arrangements designed for radiotelegraphic transmission of a special character, without publishing the particulars of these arrangements.

Article 8.

The working of radiotelegraphic stations shall be organized, as far as possible, in such a manner as not to interfere with the working of other stations of the kind.

Article 9.

Radiotelegraph stations are bound to accept with absolute priority calls of distress from ships, to answer such calls with similar priority, and to take the necessary steps with regard to them.

Article 10.

The total charge for radiotelegrams comprises :—

(1) The charge proper to the transmission oversea, viz. :

(*a*) The "coast charge" which belongs to the coast station.

(*b*) The "ship charge" which belongs to the ship station.

(2) The charge for transmission over the lines of the telegraph system, calculated according to the general rules.

The rate of the coast charge is subject to the approval of the Government to whose authority the coast station is subject, and the rate of the ship charge to the approval of the Government whose flag the ship flies.

Each of these two charges shall be fixed according to a tariff per word pure and simple, with the option of fixing a minimum charge per telegram, on the basis of an equitable remuneration for the radiotelegraphic work. Each of these charges must not exceed a maximum to be fixed by the High Contracting Parties.

Nevertheless, each of the High Contracting Parties has the right to authorize charges exceeding this maximum in the case of stations of a range exceeding 800 kilometres, or of stations which are exceptionally costly by reason of the material conditions of their installation and working.

As regards radiotelegrams originating in or destined for a country with whose coast stations they are directly exchanged, the High Contracting Parties shall acquaint one another mutually with the charges applicable to transmission over the lines of their telegraph systems. The charges shall be those which follow from the principle that the coast station is to be regarded as the station of origin or of destination.

Article 11.

The provisions of the present Convention are completed by Regulations which have the same validity and come into force at the same time as the Convention.

The provisions of the present Convention and of the Regulations relative thereto may be modified at any time by the High Contracting Parties by common consent. Conferences of Plenipotentiaries or simple administrative Conferences, according as the Convention or the Regulations are in question, shall take place periodically; each Conference will itself fix the place and date of the following Conference.

Article 12.

These Conferences shall be composed of delegates of the Governments of the contracting countries.

In the deliberations, each country shall have one vote only.

If a Government adheres to the Convention for its Colonies, Possessions, or Protectorates, subsequent Conferences may determine

that the whole or a part of these Colonies, Possessions, or Protectorates is to be regarded as forming a Country for the purposes of the foregoing paragraph.

But the number of votes which one Government, including its Colonies, Possessions, or Protectorates, may exercise cannot exceed six.

Article 13.

An International Bureau shall be entrusted with the duty of collecting, arranging, and publishing information of every kind relative to radiotelegraphy; of circulating in proper form proposals for the modification of the Convention and Regulations; of notifying the alterations adopted, and, generally, of carrying out any work bearing on matters of administration which may be assigned to it in the interests of international radiotelegraphy.

The expenses of this institution shall be borne by all the contracting countries.

Article 14.

Each of the High Contracting Parties reserves the right of prescribing the conditions on which it admits radiotelegrams from or to a station—whether ship or coast—which is not subject to the provisions of the present Convention.

If a radiotelegram is admitted, the ordinary charges must be applied to it.

Every radiotelegram originating at a ship station and received by a coast station of a contracting country, or accepted in transit by the Administration of a contracting country, must be sent forward.

Every radiotelegram intended for a ship must also be sent forward if the Administration of a contracting country has accepted it from the sender, or if the Administration of a contracting country has accepted it in transit from a non-contracting country, subject to the right of the coast station to refuse to transmit it to a ship station belonging to a non-contracting country.

Article 15.

The provisions of Articles 8 and 9 of this Convention are also applicable to radiotelegraph installations other than those indicated in Article 1.

Article 16.

Governments which have not taken part in the present Convention shall be allowed to adhere thereto at their request.

This adhesion shall be notified through the diplomatic channel to the contracting Government under whose auspices the last Conference has been held, and by it to all the others.

Adhesion involves as a matter of right acceptance of all the clauses of the present Convention and admission to all the advantages stipulated therein.

Article 17.

The provisions of Articles 1, 2, 3, 5, 6, 7, 8, 11, 12, and 17 of the International Telegraph Convention of St. Petersburg of July 10–22, 1875, are applicable to international radiotelegraphy.

Article 18.

In case of difference between two or more of the contracting Governments concerning the interpretation or execution of the present Convention or of the Regulations provided for in Article 11, the question at issue may, by common consent, be submitted to arbitration. In that event, each of the Governments concerned shall choose another not interested in the question.

The decision of the arbitrators shall be determined by an absolute majority of votes.

In the event of an equality of votes, the arbitrators shall choose, in order to settle the difference, another contracting Government, also without interest in the question. In default of agreement as to this choice, each arbitrator shall propose another disinterested contracting Government; and lots shall be drawn between the Governments proposed. The drawing of the lots appertains to the Government on whose territory the International Bureau provided for in Article 13 carries on its work.

Article 19.

The High Contracting Parties undertake to carry out or to propose to their respective Legislatures the measures necessary to ensure the execution of the present Convention.

Article 20.

The High Contracting Parties shall communicate to one another the laws which may have already been adopted or which may hereafter come into force in their countries relative to the subject-matter of the present Convention.

Article 21.

The High Contracting Parties retain their full liberty concerning radiotelegraph installations not covered by Article 1, and, in particular, concerning naval and military installations, which are subject only to the obligations of Articles 8 and 9 of the present Convention.

Nevertheless, when these installations carry on public correspondence, they shall conform, for the performance of this service, to the stipulations of the Regulations so far as concerns the manner of transmission and the accounting.

Article 22.

The present Convention shall come into operation on and from the 1st July, 1908, and shall remain in force for an indefinite period, or until the expiration of a year from the date of its denunciation.

Denunciation only takes effect as regards the Government in whose name it is made. The Convention shall remain in force as regards the other Contracting Parties.

Article 23.

The present Convention shall be ratified and the ratifications shall be deposited at Berlin with as little delay as possible.

In witness whereof the respective Plenipotentiaries have signed the Convention in a single copy, which will remain deposited in the archives of the Imperial German Government, and of which a copy will be sent to each Party.

Done at Berlin, the 3rd November, 1906.

ADDITIONAL UNDERTAKING.

The undersigned Plenipotentiaries of the Governments of the United States of America, the Argentine Republic, Austria Hungary, Belgium, Brazil, Bulgaria, Chili, Denmark, France, Germany, Greece, Monaco, the Netherlands, Norway, Roumania, Russia, Spain, Sweden, Turkey, and Uruguay undertake to apply the provisions of the following additional Articles on and from the date on which the Convention comes into force :—

I.

Each ship station indicated in Article 1 of the Convention shall be bound to intercommunicate with every other ship station without regard to the particular system of radiotelegraphy adopted by these stations respectively.

II.

The Governments which have not adhered to the above Article may at any time make it known, by adopting the procedure indicated in Article 16 of the Convention, that they undertake to apply its provisions.

Those which have adhered to the above Article may at any time make known, under the conditions prescribed in Article 22 of the Convention, their intention of ceasing to apply its provisions.

III.

The present undertaking shall be ratified and the ratifications shall be deposited at Berlin with as little delay as possible.

In witness whereof the respective Plenipotentiaries have signed the present undertaking in a single copy, which will remain deposited in the archives of the Imperial German Government, and of which a copy will be sent to each Party.

Done at Berlin, the 3rd November, 1906.

FINAL PROTOCOL.

At the moment of proceeding to the signature of the Convention adopted by the International Radiotelegraphic Conference at Berlin, the undersigned Plenipotentiaries have agreed as follows:—

I.

The High Contracting Parties agree that at the next Conference the number of votes which each country shall have (Article 12 of the Convention) shall be determined at the outset of the deliberations, so that the Colonies, Possessions, or Protectorates admitted to the enjoyment of votes may be able to exercise their right of voting throughout all the proceedings of that Conference.

The decision arrived at shall have immediate effect, and shall remain in force until it is varied by a later Conference.

So far as the next Conference is concerned, the proposals for the admission of new votes in favour of Colonies, Possessions, or Protectorates which may have adhered to the Convention shall be addressed to the International Bureau six months at least before the date of meeting of that Conference. These proposals shall immediately be notified to the other contracting Governments, which may, within a period of two months from the receipt of the notification, put forward similar proposals.

II.

Each contracting Government may reserve the power of designating, according to circumstance, certain coast stations which shall be exempt from the obligation proposed by Article 3 of the Convention, on condition that, on and from the application of this provision, there shall be open on its territory one or more stations subject to the obligations of Article 3 and provided for the radiotelegraphic service in the region served by the exempted stations in such a manner as to satisfy the requirements of public correspondence. The Governments which wish to reserve this power must notify their desire in the form prescribed in the second paragraph of Article 16 of the Convention, not later than three months before the Convention comes into operation, or in case of later adhesions, at the moment of adhesion.

The countries whose names appear below declare at once, that they will not reserve this power:—

United States of America.
Argentine Republic.
Austria.
Hungary.
Belgium.
Brazil.
Bulgaria.
Chili.
Germany.
Greece.
Mexico.
Monaco.
Netherlands.
Norway.
Roumania.
Russia.
Sweden.
Uruguay.

III.

The manner of carrying out the provisions of the preceding Article is left to the Government which avails itself of the right of exemption; this Government has full liberty to decide, from time to time, according to its own judgment, how many and what stations shall be exempted. This Government has the same liberty in regard to the manner of carrying out the condition relative to the keeping open of other stations subject to the obligations of Article 3 and providing for the radiotelegraphic service in the region served by the exempted station in such a manner as to satisfy the requirements of public correspondence.

IV.

It is understood that, in order that scientific progress may not be impeded, the provisions of Article 3 of the Convention do not prevent the possible use of a system of radiotelegraphy incapable of communicating with other systems, provided always that this incapacity is due to the specific nature of the system, and is not the result of arrangements adopted solely with the view to prevent intercommunication.

V.

The adhesion to the Convention of the Government of a country having Colonies, Possessions, or Protectorates does not imply the adhesion of its Colonies, Possessions, or Protectorates in the absence of a declaration to that effect on the part of such Government. A separate adhesion or a separate denunciation may be made in repect to the whole of such Colonies, Possessions or Protectorates, taken together or in respect of each of them separately, under the conditions laid down in Articles 16 and 22 of the Convention.

It is understood that stations on board ships having their port of registry in a Colony, Possession, or Protectorate may be deemed to be subject to the authority of such Colony, Possession, or Protectorate.

VI.

Note has been taken of the following declaration :—

The Italian delegation, while signing the Convention, must nevertheless make the reservation that the Convention can only be ratified by Italy at the date of expiration of its contracts with Mr. Marconi and his Company, or at an earlier date if the Italian Government is able to arrange accordingly by negotiation with Mr. Marconi and his Company.

VII.

The Convention, in the event of one or more of the High Contracting Parties not ratifying it, shall be none the less valid for the Parties which shall have ratified it.

In witness whereof, the undermentioned Plenipotentiaries have

drawn up the present Final Protocol, which shall have the same force and the same validity as if its provisions were inserted in the actual text of the Convention to which it relates, and they have signed it in a single copy, which will remain deposited in the archives of the Imperial German Government, and of which a copy will be sent to each Party.

Done at Berlin, the 3rd of November, 1906.

REGULATIONS.

The following are the Service Regulations annexed to the International Radiotelegraphic Convention.

1. Organization of Radiotelegraph Stations.

I.

The choice of the radiotelegraphic apparatus and arrangements to be used by coast stations and ship stations is unrestricted. The installation of these stations must keep pace as far as possible with scientific and technical progress.

II.

Two wave-lengths, one of 300 and the other of 600 metres, are allowed for general public correspondence. Every coast station open for this service employs one or other of these two wave-lengths. During the whole period for which it is open for service, every station must be in a position to receive calls made by means of its own wave-length, and it must not make use of any other wave-length for the service of general public correspondence. Nevertheless, each Government may authorize the use at any coast station of other wave-lengths for the purpose of providing a long-distance service, or a service other than that of general public correspondence, established in accordance with the provisions of the Convention, on condition that these wave-lengths do not exceed 600 metres or do exceed 1600 metres.

III.

1. The normal wave-length for ship stations is 300 metres. Every ship station must be installed in such a way as to be capable of using this wave-length. Other wave-lengths may be used by these stations on condition that they do not exceed 600 metres.

2. Ships of small tonnage, which it would be materially impossible to equip with plant producing a wave-length of 300 metres, may be authorized to use a shorter wave-length.

IV.

1. By the agency of the International Bureau, a list shall be prepared of the radiotelegraph stations indicated in Article 1 of the

Convention. This list shall give the following particulars regarding each station :—

(i.) Name, nationality, and geographical position in the case of coast stations; name, nationality, distinguishing signal under the International Code, and indication of the ship's port of registry, in the case of ship stations.

(ii.) Call-signal (the call-signals must be distinguished from one another, and must be each composed of a group of three letters).

(iii.) Normal range.

(iv.) System of radiotelegraphy.

(v.) Nature of receiving apparatus (recording, sound-reading, or other apparatus).

(vi.) Wave-lengths used by the station (the normal wave-length is underlined).

(vii.) Nature of the service performed by the station :—

General public correspondence;

Restricted public correspondence (correspondence with the ships . . . correspondence with the shipping lines . . . correspondence with ships equipped with apparatus of the . . . system, etc.);

Long-distance public correspondence;

Private correspondence of the owners of the station;

Special correspondence (correspondence of an exclusively official nature), etc.

(viii.) Hours of service.

(ix.) Coast or ship charge.

2. The list shall also comprise such particulars with regard to radiotelegraph stations other than those indicated in Article 1 of the Convention as are communicated to the International Bureau by the administration to whose authority these stations are subject.

V.

The stations indicated in Article 1 of the Convention are prohibited from exchanging superfluous signals and words. Trials and practice are only permitted at these stations in so far as they do not interfere with the service of other stations.

VI.

1. No ship station may be established or worked by any private enterprise without the authorization of the Government to whose authority the ship is subject. This authorization is given by a licence issued by that Government.

2. Every ship station which is authorized must satisfy the following conditions :—

(*a*) The system used must be a syntonized system;

(*b*) The speed of transmission and reception must, in normal circumstances, not be less than twelve words a minute, five letters being counted as one word;

(*c*) The power imparted to the radiotelegraphic apparatus must

not, in normal circumstances, exceed one kilowatt. Power in excess of one kilowatt may be used if the ship finds it necessary to exchange messages at a distance of more than 300 kilometres from the nearest coast station, or if, by reason of intervening obstacles, communication can only be effected by an increase of power.

3. The service of the ship station must be carried on by a telegraphist holding a certificate issued by the Government to whose authority the ship is subject. This certificate testifies to the technical proficiency of the telegraphist as regards—

(*a*) The adjustment of apparatus ;

(*b*) Transmission and sound-reading at a speed which must not fall short of 20 words a minute ;

(*c*) Knowledge of the regulations applicable to the exchange of radiotelegraphic traffic.

4. In addition, the certificate testifies that the Government has bound the telegraphist to the obligation of preserving the secrecy of correspondence.

VII.

1. If an Administration has information of a breach of the Convention or of the Regulations committed at one of the stations which it has authorized, it shall verify the facts and fix the responsibility.

In the case of ship stations, if the responsibility falls on the telegraphist, the Administration shall take the necessary steps, and, if need be, withdraw his certificate. If it is proved that the breach was due to the condition of the apparatus, or to instructions given to the telegraphist, similar steps shall be taken with regard to the licence granted to the ship.

2. In the event of repeated breaches by the same ship, if the representations made to the Administration to whose authority the ship is subject by another Administration remain without effect, the latter is empowered, after giving notice, to authorize its coast stations to refuse communications from the ship in question. In case of difference between the two Administrations, the question shall be submitted to arbitration at the instance of one of the Governments in question. The procedure followed shall be that indicated in Article 18 of the Convention.

2. Duration of Service at Coast Stations.

VIII.

1. The service at coast stations is, as far as possible, permanent, day and night, without interruption.

Nevertheless, certain coast stations may provide a service of limited duration. Each Administration fixes the hours of service.

2. Those coast stations at which the service is not permanent must not close before they have transmitted all their radiotelegrams to such ships as are within their range of transmission, and have

received from these ships all the radiotelegrams of which notice has been given. This provision applies also when ships notify their presence before work has actually ceased.

3. Form and Acceptance of Radiotelegrams.

IX.

If part of the route followed by a radiotelegram lies over telegraph lines or through radiotelegraph stations belonging to a non-contracting country, the radiotelegram may be forwarded on condition that the Administrations of the country to which these lines or stations belong have at the least declared their willingness to apply, when occasion arises, those provisions of the Convention and Regulations which are essential for the proper disposal of radiotelegrams, and provided also that adequate arrangements are made for accounting.

X.

1. Radiotelegrams bear the service instruction "Radio" in the preamble.

2. In the transmission of radiotelegrams from ship stations to coast stations the date and the time of handing in are omitted from the preamble.

On retransmission over the ordinary telegraph system the coast station inserts, as the indication of the office of origin, its own name followed by that of the ship, and gives as the time of handing in, the time of receipt.

XI.

The address of radiotelegrams for ships at sea should be as complete as possible. It must contain the following:—

(*a*) Name of addressee, with further particulars, if necessary.
(*b*) Name of ship as it appears in the list, supplemented, in the case of ships bearing the same name, by the nationality of the ship, and, if necessary, its distinguishing signal under the International Code.
(*c*) Name of coast station as it appears in the list.

4. Charges.

XII.

The coast charge must not exceed 60 centimes a word, nor the ship charge 40 centimes a word.

A minimum not exceeding the coast charge or the ship charge for a radiotelegram of 10 words may be fixed either for the coast charge or for the ship charge.

XIII.

A country on whose territory a coast station is established which serves as a medium for the exchange of radiotelegrams between a

ship station and another country is considered, for the purpose of applying the telegraph rates, as the country of origin or of destination of those radiotelegrams and not as a country of transit.

5. Collection of Charges.

XIV.

The whole charge for radiotelegrams is collected from the sender.

For this purpose ship stations must have the necessary tariffs. Nevertheless they have the right to obtain information from coast stations with regard to the assessment of the charge for radiotelegrams in respect of which they do not possess all the requisite particulars.

6. Transmission of Radiotelegrams.

(*a*) *Signals.*

XV.

The signals used are those of the International Morse Code (see p. 636).

XVI.

Ships in distress make use of the following signal:—

– – –   —— —— ——   – – –

repeated at short intervals.

As soon as a station perceives the signal of distress it must suspend all correspondence, and must not resume work until it has made sure that the communication consequent upon the call for assistance has been completed.

When a ship in distress adds, after a series of signals of distress, the call-signal of a particular station, the duty of answering the call rests with that station only. Failing any mention of a particular station in the signal of distress, every station which perceives the call is bound to answer it.[1]

XVII.

1. The call-signal followed by the letters "PRB"

– —— —— –   – —— –   —— – – –

signifies that the ship or the station making the call wishes to communicate with the station called by means of the International Code of Signals.

The combination of the letters "PRB" is prohibited, as a service signal, for any other purpose than that above indicated.

2. The International Code of Signals may be used for radiotelegrams.

Those which are addressed to a radiotelegraph station for onward transmission are not translated by that station.

[1] This signal, S, O, S, has superseded the Marconi Company's original high sea cry for help, which was C, Q, D.

(*b*) *Order of Transmission.*

XVIII.

Between two stations radiotelegrams of the same rank are transmitted separately in alternate order or in series consisting of several radiotelegrams, as may be determined by the coast station, provided that the time occupied in the transmission of any one series does not exceed 20 minutes.

(*c*) *Calling of Radiotelegraph Stations and Transmission of Radiotelegrams.*

XIX.

1. As a general rule, it is the ship station which calls the coast station.

2. The call must only be made, as a general rule, when the distance of the ship from the coast station is less than 75 per cent. of the normal range of the latter.

3. Before beginning to call, the ship station must adjust its receiving apparatus to the highest possible degree of sensitiveness and make sure that the coast station which it wishes to call is not engaged in communication. If it finds that transmission is taking place it awaits the first break.

4. The ship station uses, for calling purposes, the normal wave-length of the coast station.

5. If in spite of these precautions the exchange of public radiotelegraphic traffic is interfered with, the call must cease at the first request made by a coast station open for public correspondence. This station must then indicate approximately how long it will be necessary to wait.

XX.

1. The call comprises the signal —— – —— – ——, the call-signal of the coast station thrice repeated, the word "de" followed by the call-signal of the transmitting station thrice repeated.

2. The station called answers by giving the signal

—— – —— – ——,

followed by the call-signal of the calling station thrice repeated, by the word "de," by its own call-signal, and by the signal

—— – ——.

XXI.

If a station called does not reply as the result of the call (Article XX.) thrice repeated at intervals of two minutes, the call can only be renewed after an interval of half an hour, the station making the call having first ascertained that no radiotelegraphic communication is in progress.

XXII.

1. As soon as the coast station has answered, the ship station makes known—

(*a*) The distance of the ship from the coast station in nautical miles.

(*b*) Its true bearings in degrees reckoned from 0 to 360.

(*c*) Its true course in degrees reckoned from 0 to 360.

(*d*) Its speed in nautical miles.

(*e*) The number of words which it has to transmit.

2. The coast station replies by indicating the number of words which it has to transmit to the ship.

3. If transmission cannot take place at once the coast station informs the ship station approximately how long it will be necessary to wait.

XXIII.

When a coast station receives calls from several ship stations, the coast station decides the order in which the ship stations shall be allowed to transmit their correspondence.

The sole consideration which must govern the coast station in settling this order is the necessity of allowing every station concerned to exchange the greatest possible number of radiotelegrams.

XXIV.

Before beginning the exchange of correspondence the coast station informs the ship station whether transmission is to take place in alternate order or in series (Article XVIII.), it then begins transmission or follows up these service instructions with the signal —— – —— (invitation to transmit).

XXV.

The transmission of a radiotelegram is preceded by the signal —— – —— – —— and terminated by the signal

– —— – —— –

followed by the call-signal of the transmitting station.

XXVI.

When the radiotelegram to be transmitted contains more than 40 words, the transmitting station interrupts transmission after each series of about 20 words with a mark of interrogation

– – —— —— – –,

and only continues transmission after having obtained from the receiving station the repetition of the last word duly received, followed by a mark of interrogation.

In the case of transmission by series, an acknowledgment of receipt is given after each radiotelegram.

XXVII.

1. When the signals become doubtful, it is important that recourse should be had to all possible means for effecting transmission. For this purpose the radiotelegram is repeated at the request of the receiving station, but not more than three times. If in spite of this triple transmission the signals are still unreadable, the radiotelegram is cancelled. If an acknowledgment of receipt is not received, the transmitting station again calls the receiving station. If no reply is made after three calls, transmission is not continued.

2. If the receiving station, in spite of defective reception, thinks that the radiotelegram may be delivered, it inserts the service instruction "Reception doubtful" at the end of the preamble, and sends on the radiotelegram.

XXVIII.

All stations are bound to exchange traffic with the minimum expenditure of energy required for obtaining effective communication.

(*d*) *Acknowledgment of Receipt and End of Work.*

XXIX.

1. The acknowledgment of receipt is given in the form prescribed by the International Telegraph Regulations preceded by the call-signal of the transmitting station and followed by the call-signal of the receiving station.

2. The end of work between two stations is indicated by each station by means of the signal – – – —— – —— followed by its call-signal.

(*e*) *Route to be followed by Radiotelegrams.*

XXX.

1. As a general principle, the ship station transmits its radiotelegrams to the nearest coast station.

2. Nevertheless, a sender on board ship is at liberty to indicate the coast station by which he desires his radiotelegram to be dispatched.

The ship station then waits until this coast station becomes the nearest. If this condition cannot be fulfilled, the sender's wishes are only complied with if transmission can be effected without interfering with the service of other stations.

7. Delivery of Radiotelegrams.

XXXI.

When for any reason whatever a radiotelegram from a ship at sea cannot be delivered to the addressee, an advice of non-delivery is sent.

This advice is transmitted, if possible, to the ship. When a radiotelegram reaching a ship station cannot be delivered, that station informs the office of origin by means of a service advice. This advice is transmitted, as far as possible, to the coast station through which the radiotelegram has been received, or, if the circumstances require it, to the nearest coast station.

XXXII.

If the ship to which a radiotelegram is addressed has not notified its presence to the coast station within the period indicated by the sender, or, failing such indication, before the morning of the 29th day, the coast station advises the sender to that effect.

The latter has the right to request, by a paid telegraphic or postal service message addressed to the coast station, that his radiotelegram may be retained for a further period of 30 days for transmission to the ship, and so on. Failing a request to this effect, the radiotelegram is treated as undeliverable at the end of the 30th day (the day of handing in not included).

Nevertheless, if the coast station knows that the ship has passed beyond its range of transmission before the radiotelegram could be transmitted to it, that station advises the sender accordingly.

8. Special Telegrams.

XXXIII.

The following are not admitted:—

(*a*) Telegrams with prepaid replies.
(*b*) Telegraph Money Orders.
(*c*) Collated telegrams.
(*d*) Telegrams with acknowledgment of receipt.
(*e*) Telegrams "to follow."
(*f*) Paid service telegrams, except as regards transmission over the ordinary telegraph system.
(*g*) Urgent telegrams, except as regards transmission over the ordinary telegraph system, subject to the provisions of the International Telegraph Regulations.
(*h*) Telegrams to be delivered by express or by post.

9. Records.

XXXIV.

The originals of radiotelegrams and the documents relating to them retained by the Administrations or private enterprises are preserved for at least twelve months, reckoned from the month following that of handing in, with all necessary precautions to secure secrecy.

These originals and documents are, as far as possible, sent at least once a month by ship stations to the Administrations to whose authority they are subject.

10. Refunds and Reimbursements.

XXXV.

1. Refunds and reimbursements are governed by the provisions of the International Telegraph Regulations, regard being had to the restrictions indicated in Article XXXIII. of the present Regulations and subject to the following reservations:—

The time occupied in transmission by radiotelegraphy, and the time during which the radiotelegram remains at the coast station or at the ship station, are not reckoned towards the periods of delay which give rise to refunds and reimbursements.

The reimbursement is borne by the different Administrations or private enterprises which have taken part in the transmission of the radiotelegram, each Administration foregoing its proportion of the charge. Nevertheless, radiotelegrams which come under Articles 7 and 8 of the Convention of St. Petersburg remain subject to the provisions of the International Telegraph Regulations, except when it is due to an error of service that such radiotelegrams have been accepted.

2. When the acknowledgment of receipt of a radiotelegram has not reached the station which transmitted the radiotelegram, the charge is only refunded after it has been proved that the radiotelegram is one which gives rise to reimbursement.

11. Accounts.

XXXVI.

1. The coast and ship charges do not enter into the accounts for which provision is made in the International Telegraph Regulations.

The accounts relating to these charges are settled by the Administrations of the Governments concerned. They are prepared by the Administrations responsible for the coast stations and are communicated by them to the Administrations concerned.

2. In respect of transmission over the ordinary telegraph system a radiotelegram is treated, for accounting purposes, in accordance with the International Telegraph Regulations.

3. In respect of radiotelegrams from ships, the Administration responsible for the ship station is debited by the Administration responsible for the coast station with the coast and ordinary telegraph charges collected on board the ship.

In respect of radiotelegrams addressed to ships, the Administration which has collected the charges is debited directly by the Administration responsible for the coast station with the coast and ship charges. The latter Administration credits the Administration responsible for the ship with the ship charge.

Nevertheless, in cases where the Administration which has collected the charges is that responsible for the ship station, the ship charge is not debited by the Administration responsible for the coast station.

4. The monthly accounts on which the special accounting in

respect of radiotelegrams is based are prepared radiotelegram by radiotelegram, with all the necessary particulars, within six months from the month to which they relate.

5. The Governments reserve the right of making between themselves and in their dealings with private enterprises (organizations working radiotelegraph stations, shipping companies, etc.) special arrangements for the adoption of other methods of accounting.

12. International Bureau.

XXXVII.

The International Bureau of Telegraph Administrations will be entrusted, subject to the consent of the Government of the Swiss Confederation and to the approval of the Telegraph Union, with the functions specified in Article 13 of the Convention.

The additional expenses resulting from the exercise by the International Bureau of its functions in respect of radiotelegraphy must not exceed 40,000 francs per annum, not including extraordinary expenditure occasioned by the assembling of an International Conference.

These expenses form the subject of a special account, and the provisions of the International Telegraph Regulations are applicable to them. Nevertheless, pending the meeting of the Conference, each contracting Government shall notify to the International Bureau the class in which it wishes to be included.

XXXVIII.

The various Administrations shall supply the International Bureau with a Return in conformity with the annexed model, containing the particulars specified therein in respect of the stations indicated in Article IV. of the Regulations. Subsequent modifications and additions shall be communicated by the Administrations to the International Bureau between the 1st and 10th of each month. By means of the information thus communicated the International Bureau shall prepare a list and keep it up to date. The list and its supplements shall be printed and distributed to the Administrations concerned; they may also be sold to the public at cost price.

The International Bureau shall take care that the same call-signals are not adopted for different radiotelegraph stations.

13. Miscellaneous Provisions.

XXXIX.

The Administrations shall facilitate arrangements for communicating to such maritime news agencies as they think fit such information respecting wrecks and shipping casualties or of general interest for purposes of navigation, as can properly be communicated to them by their coast stations.

XL.

Traffic exchanged between the ship stations indicated in Article 1 of the Convention must be so regulated as not to interfere with the service of coast stations, the latter being entitled as a general rule to priority for purposes of public correspondence.

XLI.

1. In the absence of special arrangements between the parties concerned, the provisions of the present regulations are applicable, by analogy, to the exchange of radiotelegraphic traffic between two ships at sea, with the following exceptions:—

(*a*) Article XIV.—The ship charge accruing to the transmitting ship is collected from the sender, and that accruing to the receiving ship is collected from the addressee.

(*b*) Article XVIII.—The order of transmission is settled on each occasion by mutual agreement between the communicating stations.

(*c*) Article XXXVI.—The charges in respect of the radiotelegrams in question do not enter into the accounts provided for in Article XXXVI., these charges being retained by the Administrations which have collected them.

2. The retransmission of radiotelegrams exchanged between ships at sea is subject to special arrangements between the parties concerned.

XLII.

The provisions of the International Telegraph Regulations are applicable, by analogy, to radiotelegraphic correspondence in so far as they are not inconsistent with the provisions of the present Regulations.

In conformity with Article 11 of the Convention of Berlin, these Regulations will come into force on the 1st July, 1908.

In witness whereof the respective Plenipotentiaries have signed the Regulations in a single copy, which will remain deposited in the archives of the Imperial German Government, and of which a copy will be sent to each Party.

Done at Berlin, the 3rd November, 1906.

APPENDIX III

THE BIBLIOGRAPHY OF RADIOTELEGRAPHY

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APPENDIX IV

TABLE OF HYPERBOLIC LOGARITHMS OF NUMBERS FROM 1 TO 100

No.	Logarithm.	No.	Logarithm.	No.	Logarithm.
2	0·69314718	35	3·55534806	68	4·21950771
3	1·09861229	36	3·58351894	69	4·23410650
4	1·38629436	37	3·61091791	70	4·24849524
5	1·60943791	38	3·63758616	71	4·26267988
6	1·79175947	39	3·66356165	72	4·27666612
7	1·94591015	40	3·68887945	73	4·29045944
8	2·07944154	41	3·71357207	74	4·30406509
9	2·19722458	42	3·73766962	75	4·31748811
10	2·30258509	43	3·76120012	76	4·33073334
11	2·39789527	44	3·78418963	77	4·34380542
12	2·48490665	45	3·80666249	78	4·35670883
13	2·56494936	46	3·82864140	79	4·36944785
14	2·63905733	47	3·85014760	80	4·38202663
15	2·70805020	48	3·87120101	81	4·39444915
16	2·77258872	49	3·89182030	82	4·40671925
17	2·83321334	50	3·91202301	83	4·41884061
18	2 89037176	51	3·93182563	84	4·43081680
19	2·94443898	52	3·95124372	85	4·44265126
20	2·99573227	53	3·97029191	86	4·45434730
21	3·04452244	54	3·98898405	87	4·46590812
22	3·09104245	55	4·00733319	88	4·47733681
23	3·13549422	56	4·02535169	89	4·48863637
24	3·17805383	57	4·04305127	90	4·49980967
25	3·21887582	58	4·06044301	91	4·51085951
26	3·25809654	59	4·07753744	92	4·52178858
27	3·29583687	60	4·09434456	93	4·53259949
28	3·33220451	61	4·11087386	94	4·54329478
29	3·36729583	62	4·12713439	95	4·55387689
30	3·40119738	63	4·14313473	96	4·56434819
31	3·43398720	64	4·15888308	97	4·57471098
32	3·46573590	65	4·17438727	98	4·58496748
33	3·49650756	66	4·18965474	99	4·59511985
34	3·52636052	67	4·20469262	100	4·60517019

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